Universidad Nacional de Educación a Distancia
Departamento de Informática y Automática

Doctoral Dissertation

An Integral Web-based Environment for Control Engineering Education

Héctor Vargas Oyarzún
Electronic Engineer
from Universidad de La Frontera - Chile

Submitted at

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In memory of my dear

grandmother Doraliza Alvarez

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Part I

PRELIMINARIES

1

Introduction, Objectives and Structure

Overview

This chapter introduces the main objectives of this thesis work. Firstly, it provides a review of the use of Internet-based technologies in new teaching/learning paradigms. The main challenges faced when trying to apply these new paradigms in engineering subjects are addressed. In particular, the paradigm of flexible education in a remote experimentation context is first introduced and then, the applicability of these ideas in the development of a complete remote experimentation environment through Internet is presented.

The objectives and structure of the thesis will then be described. These sections provide insights on the main goals of the dissertation and a brief description of each chapter. The final section indicates the list of sources and research projects used to support the work presented.

1.1 Introduction

Nowadays, Internet is the first tool that comes to mind whenever a student, teacher or person in general, wishes to find out more about a specific subject. The use of computers in the traditional classroom provides numerous benefits. Sharing resources and knowledge is also another advantage in a society each time more globalized in need of more flexible mechanisms to interact and collaborate. In this sense, the evolution of Internet has changed the education landscape drastically (Riva 2001, Bourne et al. 2005, Rosen 2007, Anderson 2007, Hu & Bao 2008). What was once considered "Distance Education" is now called "On-line Education" whereby the method of teaching and learning is based on the use of the Internet (at any given time or place) to complete educational activities.

A specific example of application of this new teaching model is the "National University for Distance Education" (UNED). Compared to other Spanish universities, this institution has the largest number of students due mainly to the fact that distance education allows to enrol students who can not use the traditional educational system but wish to obtain a degree or improve their professional skills without having to change their lifestyle. It is currently possible to find a wide set of universities with on-line presence around the world (OUA 2009, London-External 2009, UDIMA 2009, OU 2009, UNED 2009, Open-UA 2009, UNAD 2009, UOC 2009). This confirms the viability and the importance of *computer-assisted teaching and learning through Internet*.

The implementation of the distance learning model is not an easy task in the case of engineering and physical sciences studies (Williams 2007). In addition to the textual/multimedia information and the other resources that are required to provide the theoretical aspects in an on-line course, *hands-on laboratories* should also be included. This is particularly true in control engineering education, a field inherently interdisciplinary, where mathematics play a fundamental role, and where progress is achieved through a mix of maths, modelling, computation and experimentation (Fleming 1989, Dormido 2004, Åström 2006). In this given context, students should be able to achieve the following:

- Understand the underlying scientific model of the phenomenon studied.
- Get acquainted with the limits of this model (i.e. how does the model accurately reflect the real behaviour and to what extent it remains a basic approximation).
- Learn how to manipulate the parameters of the model to fine-tune the behaviour of the real system.

The implementation of an effective web-based educational environment for any engineering topic should cover these three aspects of the technical education: conceptual, interpretative, and operational. These should provide the student with an opportunity to become an active player in the learning process (Dormido et al. 2005a).

Flexible education in engineering

The potential of web-based experimental applications as pedagogical support tools in the learning/teaching of control engineering has been presented in many works (Hahn & Spong 2000, Cefalo et al. 2003, Casini et al. 2004, Valera et al. 2005, Eikaas et al. 2006, Gómez & García 2007, Costas et al. 2009, Brito et al. 2009). In fact, in the last decade, several academic institutions have explored the WWW to transfer their courses and experimental activities towards distributed contexts. However, most of these developments focus on technical issues related to the design and building of web-enabled applications that allow to perform practical activities through the Internet (virtual and remote laboratories). In general, these do not take into account the social context of interaction and collaboration generated in traditional hands-on laboratories (Nguyen 2007).

Indeed, direct contact with teachers and interaction with classmates are valuable resources that may lessen or even disappear when conducting hands-on experimental sessions via web-based laboratories. This suggests the necessity to include this requirement when designing, developing, and deploying a web-based experimental environment as that described in this dissertation.

Remote experimentation and flexible learning

The flexible learning paradigm is presented as an appropriate on-line learning solution for engineering students (Kazmer & Haythornthwaite 2005). In (Gillet et al. 2005), such paradigm is analyzed by the authors from three different perspectives: *pedagogical*, *technical*, and *organizational*. From a pedagogical point of view, flexible education means to provide extended access to learning resources for all the students. As a consequence, students have more liberty as to how to organize their learning activities and thus, the participation, autonomy and collaboration between the actors involved in the laboratory (teachers, tutors, and students) are enhanced.

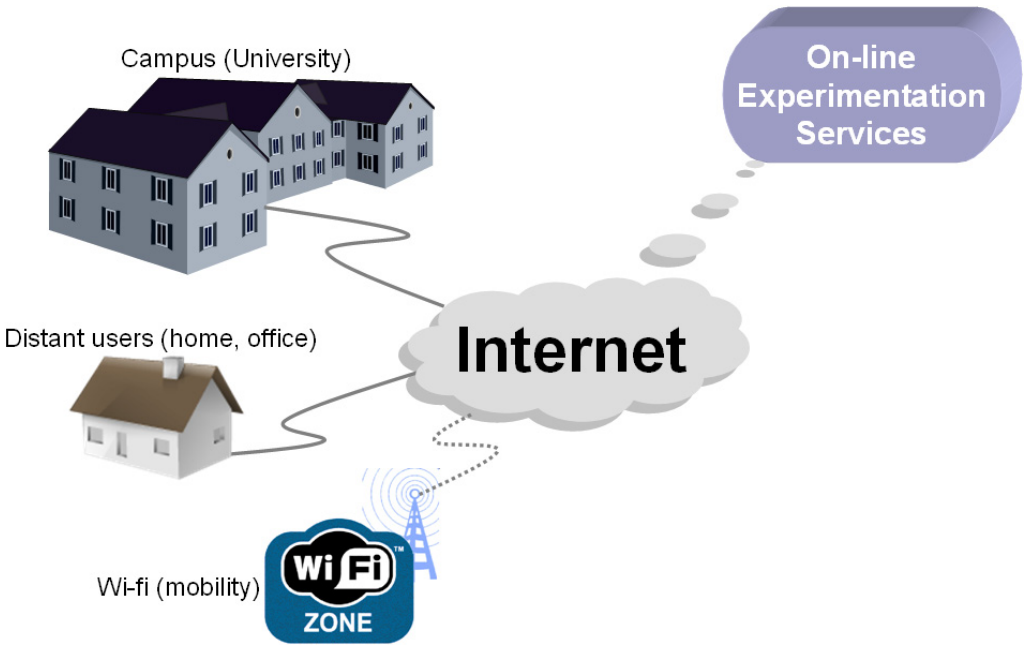


Figure 1.1: Scheme of the flexible education paradigm.

Figure 1.1 illustrates the idea of the extended accessibility. A student could follow out his/her laboratory tasks anytime-anywhere, for instance, from the campus, from home, or from any site connected to the Internet.

From a technical point of view, flexible learning means an adequate exploitation of information, communication devices, and infrastructures available, especially the Internet, and the services derived from its usage. Finally, from an organizational perspective, the flexible learning paradigm trusts in renewed cur-

ricula and the relationships and results generated through research, work and collaboration. Increased contact between researchers from different academia institutions will be achieved thanks to network infrastructures.

The flexible learning paradigm undoubtedly defines and clarifies a set of key aspects to be considered. However, an analysis of the pedagogical aspects involved should be carried out so as to clarify teaching methodology, learning resources and objectives. This, in turn, will determine both technical and organizational aspects.

Over the last years, the Department of Computer Science and Automatic Control of the UNED has been placing a great deal of effort into the analysis, design, development, and exploitation of virtual and remote laboratories for automatic control teaching and learning (Aranda et al. 1998, Sánchez 2000, Sánchez et al. 2002, Dormido 2004, Sánchez et al. 2004, Pastor et al. 2005, Dormido et al. 2005a, Sánchez et al. 2005, Duro et al. 2008). However, despite all this work, there is no appropriate environment as of yet that provides remote experimentation services through Internet to students within a holistic and structured framework. *This dissertation tries to go one step further in this direction by implementing a complete web-based integral environment to perform remote practical experiences for automatic control courses.*

On the other hand, a mix of web-based technologies and software agents (Salzmann & Gillet 2008, 2007) is commonly used to develop remote experimentation systems designed for pedagogical purposes. Incidentally, most recorded developments aimed at creating remote experimentation systems are custom-made solutions. This means, their conception, selection of software tools, and global system architecture are not simple tasks because of the wide variety of software tools available nowadays. *With regards to this aspect, the present thesis provides a structured framework to develop remote experimentation systems using three software tools*: *Easy Java Simulations* (Ejs 2009a), *LabVIEW* (LabVIEW 2009a), and *eMersion* (eMersion 2009).

Since the UNED is a distance learning university, the introduction of this kind of educational methodology is highly beneficial for students who must conjugate

work and academic life. In this context, capturing students' perception of the system developed is paramount so as to improve it and include new functions. *This dissertation also analyses the remote experimentation environment developed and provides a series of guidelines and suggestions on how to use the system and for future works.*

1.2 Objectives

The ***first objective*** of this paper is to describe the background needed to implement web-based environments to carry out hands-on laboratories through the Internet in the field of engineering education. The overall aim is to suggest a two-layered framework to create remote and virtual control laboratories and the web-based tools required to publish them on the Internet.

The ***second objective*** is to provide a new approach to create virtual and remote laboratories for control education. The approach suggested is based on the use of two software tools specifically chosen for this purpose: *Easy Java Simulations* and LabVIEW, the idea being that it will facilitate the creation of web-based labs to new developers and/or educators who wish to include this new learning paradigm in their curricula.

The ***third objective*** of this dissertation is to create a set of virtual and remote control laboratories by following the framework developed step by step. Three didactical setups located in the Automatic Control Laboratory of the UNED will be used to develop the three web-based labs: a threetank system, a temperature control system, and a DC motor. The developed prototypes will demonstrate the validity of the approach described in this work.

The ***fourth objective*** is to provide and implement the features that a flexible learning environment should offer to sustain an on-line community of web-based labs. The aim is to describe the additional web-based resources needed to support

the learning process effectively. The collaborative web-based application eMersion, specifically designed to organize and enable engineering practical activities on the Internet will be used for this purpose.

The ***fifth objective*** is to develop a web-based automatic bookings system to arrange user access of physical resources available in remote laboratories. As is the case in most academic institutions, the number of didactical setups available in laboratories is insufficient and does not match the demand of students. For cost reasons, it is possible in some cases to have one or two pilot plants available only. The reason behind the designing of an automatic bookings system is to manage user access in order to better use the physical resources.

The ***sixth and final objective*** is to evaluate the developed remote experimentation environment from the student's point of view. Two pilot experiments were carried out in order to analyze the positive and negative impact of this new way of completing the practical activities on the students.

1.3 Outlines

This thesis has been structured as follows:

Chapter 2. The typical application scenario of a remote experimentation system for pedagogical purposes is presented and discussed. This chapter also introduces the approach to follow (giving some work guidelines) in order to develop hands-on web-based laboratories.

Chapter 3. The methodology used for the implementation of virtual and remote control laboratories is presented in this dissertation. The chapter describes the JiL Server approach, a structured framework that enables to create the virtual and remote labs mentioned in this thesis by using both Easy Java Simulations and NI LabVIEW.

Chapter 4. This chapter shows how to build virtual and remote control labo-

ratories using the approach proposed in Chapter 3.

Additional information on hardware, modelling, and control of the laboratory setups used in this work is provided in Appendices A and B.

Chapter 5. Various teaching models will be analyzed that sustain and support the learning process of students in a remote experimentation context. The software tool used to publish web-based labs through Internet "eMersion" is also presented and described in detail. More information on the use of eMersion can be found in Appendix C.

Chapter 6. The analysis, design and implementation of an *Automatic Booking System* to organize and optimize the use of the physical resources available in laboratories is also presented.

The integration of this application in the remote experimentation environment eMersion is addressed in Chapter 7.

Chapter 7. The integration of the experimentation layer and learning layer is presented. All the web components described in previous chapters are coupled in order to obtain the final remote experimentation environment for engineering educational programs.

Chapter 8. An assessment system is presented in this chapter. The UNED pilot experience and the AutomatL@bs project are two experiments carried out with real students aimed at evaluating how useful the system is as a teaching tool. Results are analyzed and discussed at the end of this chapter.

Chapter 9. Conclusions and future research are presented.

1.4 Publications, Awards and Projects

Journal papers

1. H. Vargas, J. Sánchez, S. Dormido, C.A. Jara, F. Candelas, F. Torres. "Docencia en Automática: Aplicación de las TIC a la realización de actividades

prácticas a través de Internet". *Revista Iberoamericana de Automática e Informática Industrial (RIAI)*. ISSN: 1697-7912, Vol. 7, Nr. 1, pp. 35-45. Enero 2010.

2. H. Vargas, J. Sánchez, Ch. Salzmann, F. Esquembre, D. Gillet, S. Dormido (2009). "Web-enabled Remote Scientific Environments". *Computing in Science and Engineering*. vol. 11, no. 3, pp. 34-46.

3. H. Vargas, J. Sánchez, N. Duro, R. Dormido, S. Dormido-Canto, G. Farias, S. Dormido, F. Esquembre, Ch. Salzmann, D. Gillet (2008). "A systematic two-layer approach to develop Web-based experimentation environments for control engineering education". *Intelligent Automation and Soft Computing*. vol. 14, no. 4, pp. 505-524.

4. R. Dormido, H. Vargas, N. Duro, J. Sánchez, S. Dormido-Canto, G. Farías, F. Esquembre, S. Dormido (2008). "Development of a Collaborative Web-Based Control Laboratory for Automation Technicians: The Three-Tank System". *IEEE Trans on Education*. vol. 51, pp. 35-44.

5. N. Duro, R. Dormido, H. Vargas, S. Dormido-Canto, J. Sánchez, G. Farias, S. Dormido (2008). "An Integrated virtual and remote control lab: the three-tank system as a case study". *Computing in Science and Engineering*. vol. 10, pp. 50-59.

6. J. L. Guzmán, H. Vargas, J. Sánchez, M. Berenguel, S. Dormido, F. Rodríguez (2007). "Education Research in Engineering Studies: Interactivity, Virtual and Remote Labs". ISBN: 1-60021-829-6. *Book Chapter "Distance Education Research Trends", Nova Science Publisher*. pp. 131-167.

7. S. Dormido, H. Vargas, J. Sánchez, R. Dormido, N. Duro, S. Dormido-Canto, F. Morilla, M. A. Canto, G. Farias (2009). "Compartiendo recursos de experimentación a través de Internet: la experiencia Automatl@bs". *Book Chapter "La UNED ante el EEES: Redes de investigación en innovación docente 2006/2007", Editorial UNED.*

Conference papers

1. H. Vargas, Ch. Salzmann, D. Gillet, S. Dormido. "Remote Experimentation Mashup". *8th IFAC Symposium on Advances in Control Education*. Kumamoto (Japón), Octubre 2009.

2. M. Guinaldo, H. Vargas, J. Sánchez, E. Sanz, S. Dormido. "Web-based Control Laboratory: The Ball and Beam System". *8th IFAC Symposium on Advances in Control Education*. Kumamoto (Japón), Octubre 2009.

3. L. Díaz, G. Ramos, H. Vargas, R. Costa. "A Virtual/Remote Laboratory to illustrate the Internal Model Principle for periodical signals". *8th IFAC Symposium on Advances in Control Education*. Kumamoto (Japón), Octubre 2009.

4. H. Vargas, J. Sánchez y S. Dormido. "Experimentación Remota en Automática: Nuevos Entornos Basados en la Web 2.0". *XXX Jornadas de Automática*. Valladolid (España), Septiembre 2009.

5. H. Vargas, J. Sánchez y S. Dormido. "The Spanish university network of web-based laboratories for control engineering education: The AutomatL@bs project". *European Control Conference ECC 2009*. Budapest (Hungría), Agosto 2009.

6. H. Vargas, J. Sánchez y S. Dormido (2008). "Proyecto AutomatLabs: Red Interuniversitaria de Laboratorios de Control Automático a través de Internet". *XIII Latin American Congress on Automatic Control (CLCA)*. Mérida (Venezuela), November 2008.

7. H. Vargas, J. Sánchez, S. Dormido. "Acceso Extendido a Recursos de Experimentación a través de Internet: La Experiencia AutomatL@bs". *XXIX Jornadas de Automática*. Tarragona (España), Septiembre 2008.

8. G. Farias, S. Dormido, F. Esquembre, H. Vargas, S. Dormido-Canto (2008). "Laboratorio Virtual para la Enseñanza de Técnicas de Reconocimiento de

Patrones". *XIII Latin American Congress on Automatic Control (CLCA).* Mérida (Venezuela), November 2008.

9. S. Dormido, J. Sánchez, H. Vargas, S. Dormido-Canto, R. Dormido, N. Duro, G. Farias, M. A. Canto y F. Esquembre (2007). "Análisis, desarrollo y publicación de laboratorios virtuales y remotos para la enseñanza de la automática". *II Congreso Español de Informática (CEDI)*, Zaragoza (Spain).

10. J. L. Guzmán, M. Berenguel, F. Rodríguez, H. Vargas, J. Sánchez, S. Dormido (2007). "Desarrollo de un entorno de experimentación basado en web para estudios de ingeniería: un caso práctico". *II Congreso Español de Informática (CEDI)*, Zaragoza (Spain).

11. J. Sánchez, H. Vargas, S. Dormido (2007). "Web-based learning resources for vocational training on Control and measurements systems: The AutoTECH Project". *European Control Conference (ECC)*, Kos (Greece).

12. S. Dormido, J. Sánchez, F. Esquembre, H. Vargas, S. Dormido-Canto, R. Dormido, N. Duro, G. Farías, Ma. A. Canto (2007). "The development of web-based virtual laboratories using Easy Java Simulations (Ejs)". *International Conference on Remote Engineering and Virtual Instrumentation Rev07*, Oporto (Portugal).

13. H. Vargas, R. Dormido, N. Duro, J. Sánchez, G. Farías, S. Dormido, M. Canto, and F. Esquembre (2006). "Heatflow: Un laboratorio basado en Web usando Easy Java Simulations y LabVIEW para el entrenamiento en técnicas de automatización". *XII Latin American Congress on Automatic Control (CLCA).* Salvador de Bahía (Brasil).

14. G. Farías, F. Esquembre, J. Sánchez, S. Dormido, H. Vargas, S. Dormido-Canto, R. Dormido, N. Duro, and M. Canto (2006). "Desarrollo de laboratorios virtuales, interactivos y remotos utilizando Easy Java Simulations y Modelos Simulink". *XII Latin American Congress on Automatic Control (CLCA).* Salvador de Bahía (Brasil).

15. H. Vargas, J. Sánchez, R. Dormido, G. Farías, and S. Dormido (2006). "Desarrollo de laboratorios virtuales y remotos usando Easy Java Simulations and LabVIEW. El sistema Heatflow como un caso de estudio". *XXVII Jornadas de Automática*. Almería (Spain).

16. J. Sánchez, H. Vargas, S. Dormido (2006). "Recursos de Aprendizaje basados en el Web para la formación ocupacional en sistemas de Regulación y Control". *XXVII Jornadas de Automática*. Almería (Spain).

17. H. Vargas, G. Farías, S. Dormido, and J. Sánchez (2006). "Web-based learning resources for automation technicians vocational training: illustred with a Heatflow and liquid level laboratory". *7th IFAC Symposium on Advances in Control Education (ACE)*. Madrid (Spain).

18. N. Duro, R. Dormido, H. Vargas, S. Dormido, J. Sánchez, and R. Pastor (2005). "The Three Tank System: A Remote and Virtual Control Laboratory using Easy Java Simulations". *44th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC)*. Sevilla (Spain).

19. N. Duro, R. Dormido, H. Vargas, S. Dormido, J. Sánchez (2005). "El sistema de tres tanques. Un laboratorio virtual y remoto usando Easy Java Simulations". *I Spanish Congreso on Computer Sciences (CEDI/EIWISA)*. Granada (Spain).

Awards

- PRODEL prize to the best paper about "Control Education" presented in the XXIX Jornadas de Automática. Tarragona, Spain. September 2008. Title of paper: *Acceso Extendido a Recursos de Experimentación a Través de Internet: La Experiencia AutomatL@bs.*

- Prize from "Consejo Social y Fundación UNED" to the best project on teaching innovation 2008. Madrid, Spain. December 2008. Title of project: *AutomatL@bs - Red de investigación para la innovación docente en Automática mediante laboratorios virtuales y remotos.*

– Honorable mention in the final competition "Science in Action" in the modality "Science and Technology". Title of the contribution: *AutomatL@bs: Una red de laboratorios virtuales y remotos para la enseñanza en control automático*. Granada, Spain. September 2009.

Research projects

The results obtained in the framework of this dissertation have been supported by different research projects:

– *Interactive tools to the modelled, visualization, simulation and control of hybrid systems (2004–2006).* Spanish Ministry of Education and Science, CICYT (Ref. DPI2004-01804). National University for Distance Education of Madrid, Spain. Directed by Prof. Sebastián Dormido Bencomo.

– *Control of complex systems for logistic and production of goods and services. COSICOLOGI-CM (2005–2008)*, IV PRICIT. Autonomous Region of Madrid-Spain (Ref. S-0505/DPI/0391). Directed by Prof. Sebastián Dormido Bencomo.

– *Event-based modelling, simulation, and control (2007–2012).* Spanish Ministry of Education and Science, CICYT (Ref. DPI2007-61068). National University for Distance Education of Madrid, Spain. Directed by Prof. Sebastián Dormido Bencomo.

2

Environment Global Architecture

Overview

The first step before starting to develop a remote experimentation system is to define its global architecture. In this sense, from a *software engineering* point of view, there are three mandatory stages to follow in every software development process: *Requirements Analysis*, *Specifications*, and *Design and Architecture*. This chapter describes these stages and tries to give a systematic approach to use for the appropriate implementation of a web-based experimentation environment with pedagogical perspectives.

Once the global structure of the system is specified (*requirements analysis* and *specifications*), the *design and architecture* process is then addressed. Here, the global architecture of the system is divided into several sub-problems or components that form the entire system. In this given context, this chapter introduces the systematic two-layer approach to follow in the development process of the system: *the experimentation and the e-learning layers*.

2.1 Planning the structure of the system

Figure 2.1 illustrates the typical application scenario of a remote experimentation system designed for pedagogical purposes. The university provides the overall infrastructure required for remote experimentation services offered to students, that is, a set of didactical-setups specially designed for hands-on laboratories, a set of server computers used to interface these processes with the outside world and a main server computer providing the complementary web-based resources needed to use remote-labs. The system users (clients) can access experimentation services available from anywhere providing there is an Internet connection.

The above mentioned describes, in a few words, the remote experimentation context in engineering education. However, developing a complete environment able to provide such experimentation services is not an easy task. For this reason, the next section presents a systematic approach to follow to develop a system with these characteristics.

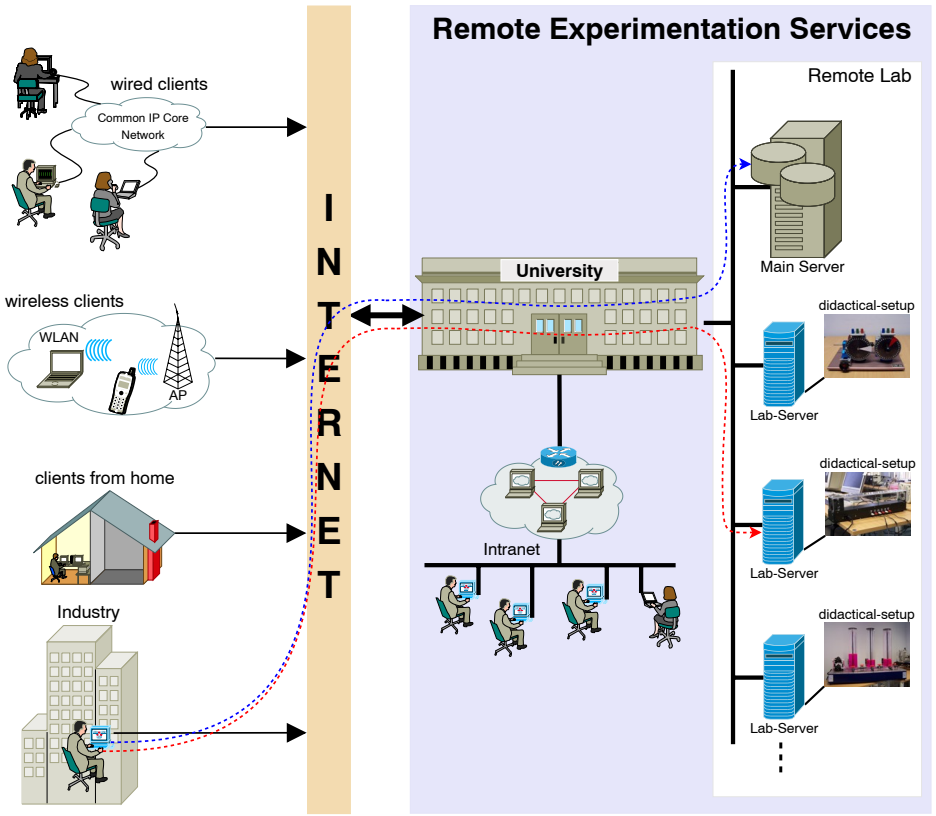


Figure 2.1: On-line experimentation system: Global architecture.

2.2 A systematic two-layer approach

Although the development responsibilities can be clasified in multiple ways, in this dissertation we have divided the problem into two levels or "layers". The first layer is the so-called *experimentation layer* that includes all the software and hardware components needed to develop the experimental applications, that is, the web-based virtual and remote laboratories. As web-based labs alone do not give us all the elements needed to provide remote experimentation services in a pedagogical context, complementary web-based resources are needed to manage the learning process of students. Thus, the so-called *e-learning layer* implies the development of the functionalities required to support the teaching and learning of students through the Internet (Vargas et al. 2008).

2.2.1 Layer 1: The experimentation layer

The *experimentation layer* wraps the design methodology and building of the graphical user interface of the client side and the server application which links to the real plant in the lab. The development process of this layer is addressed by means of the well-known *client and server structure*. Figure 2.2 illustrates the general scheme of the *experimentation layer* based on this communication architecture. From a software engineering point of view, the development process begins with the analysis of requirement and specifications of implementation.

The following subsections indicate some recommendations to follow on how to develop this layer.

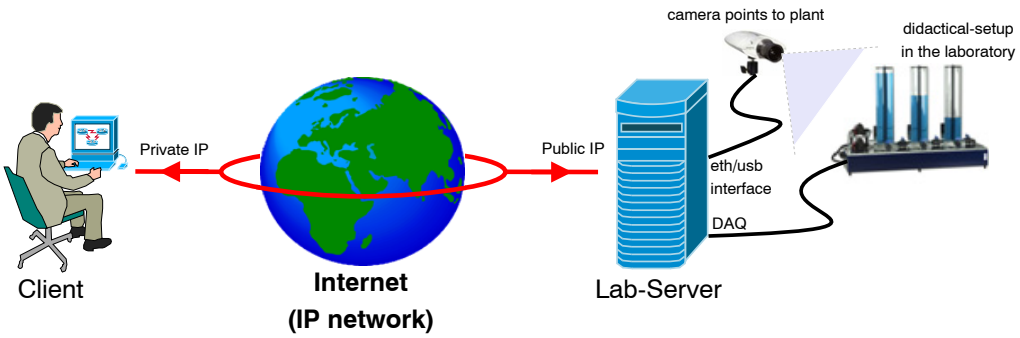


Figure 2.2: Experimentation layer: General scheme.

2.2.1.1 The client: Requirements and specifications

When we talk about the graphical user interface on the client side, we refer to the set of controls, indicators, graphical elements, and visualization components which all constitute the application the users will use to complete their experiments. In this sense, the design and building process of these interfaces must follow certain basic rules to simplify and facilitate their understanding. A set of characteristics that should be used as design options for the client side interface are described hereafter:

- The software used for developing should be multiplatform. Java shows the expected characteristics for designing this kind of applications as it provides various features as the platform independence and the simple accesibility from any web browser without additional software (only, the runtime engine JVM is needed). This means, the user only needs a web browser with Java support to access the web-based lab.

- The communication protocol used to communicate with the server-side should be low-level protocols to stream data through the Internet: TCP (Transfer Control Protocol) or UDP (User Datagram Protocol). They allow for a better control of data packet transmisions in networks based on IP protocol, such as the Internet.

- The graphical user interface must prove simple and intuitive. It should be user-friendly and it should also have been tested successfully in different environments.

- Access to the laboratory in either virtual or remote version should be enabled using the same graphical interface. In simulation mode, the state of the system and its associated variables are updated based on the evolution of a mathematical model of the process. Otherwise, in remote mode, these variables are updated according to the real plant changes in the remote location. Video feedback should be included in order to provide distant users with a certain sense of presence in the laboratory.

– Events sheduling to program faults in the system should be scheduled. The systems could be enabled to analyze systems in presence of noise or disturbances measurements. The robustness of the system could then be evaluated under these anomalous operating situations.

– Finally, it is highly recommended that users define experiments in an easy way. For example, a programmed change of the setpoint could be required to observe the process response in different operating points.

2.2.1.2 The server: Requeriments and specifications

The server side applications are running on a computer located close to the physical system equipped with the needed hardware/software interfaces to access sensors and actuators from the real plant. Additionaly, the server should implement the interfaces, protocols, and programming modules needed to connect with the outside world, i.e., with the clients (see Figure 2.3).

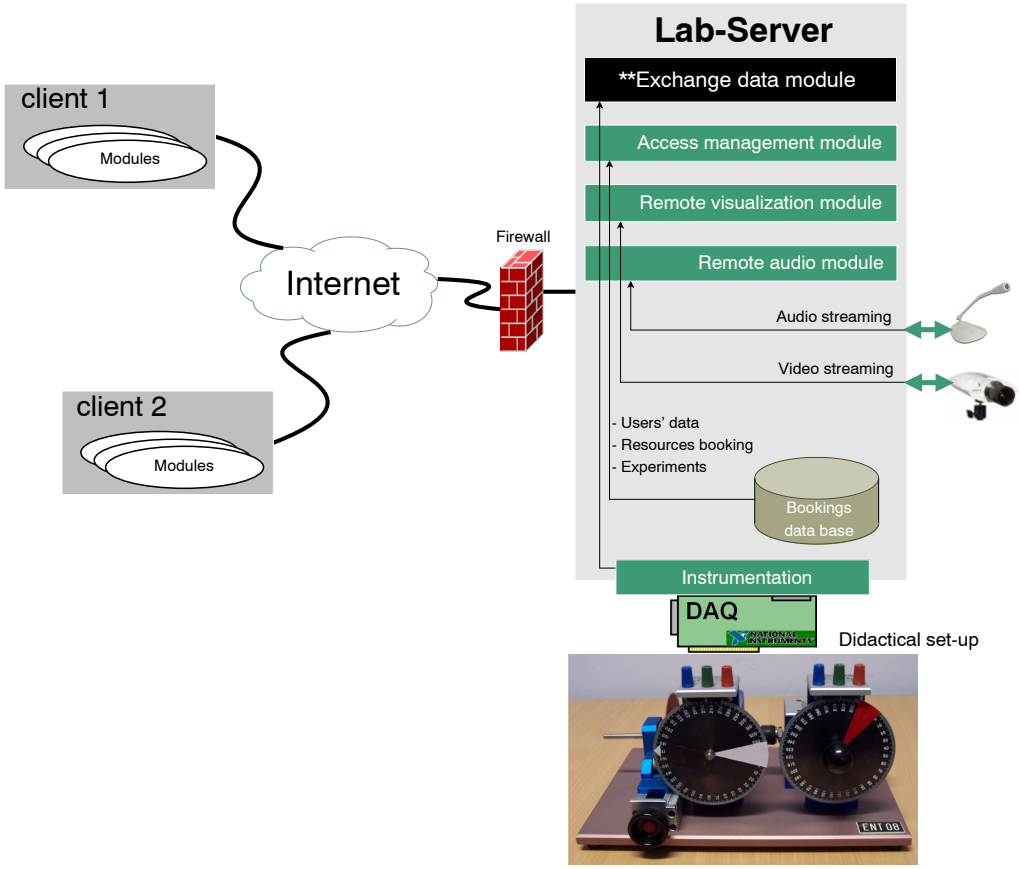


Figure 2.3: Server side implementation requirements.

Although there are a high number of hardware-software tools that can be used, for the purpose of the present dissertation we used LabVIEW from National Instruments for the implementation phase (see next chapter). From a software design point of view, the server is composed of a set of modules (some of them optional) described below:

- *A data exchange module*: This software remains in a listening state waiting for remote connections from users. It receives commands and queries from clients and makes them effective over the physical system. Responses are retrieved from the real plant through the instrumentation hardware and, finally, are sent back to the client. The link between the server and clients is established via Internet and therefore, the TCP/IP protocol suite becomes the backbone for the information exchange.
  This module, which is labelled with (**) in Figure 2.3, is of a paramount importance as it is in charge of implementing the listening server that is always waiting for remote connections from clients. Furthermore, the module acts as a gateway and input filter to the system.

- *An access management module*: This software module contains all the information related to users, timeslot bookings, and other parametrizable information. A database manager is used to handle the users' reservations and physical resources. Each register in this database corresponds to a booking scheduled for a specific time and date.

- *An instrumentation module*: This module incorporates all the hardware needed to connect the physical system with the server: amplifiers, power modules, data acquisition cards (DAQ), signal conditioning, etc.

- *A remote visualization module*: This module allows the users to examine what is happening with the physical system during its remote manipulation from a client. In order to provide this feature video cameras are used. The system must be able to transmit a sense of realism in order to encourage its usage and increase motivation whilst completing tasks.

– *An audio feedback module*: This module is optional. It would allow to further increase the sense of realism. For example, in a level control remote-lab we could transmit the ambient sound that is produced by manipulating pumps or just by listening to the water filling the tank.

Each module in the server has its counterpart in the client side. For example, to read the video streaming captured by the server, the client application must implement a new module that allows to communicate and decode the data retrieved from the remote site and then render it in the interface.

Although it is not possible to detail all of the design options available, these cover a big part of the characteristics that an experimentation environment should fulfill to satisfy pedagogical and learning requirements in practical engineering activities. More details can be found in (Sánchez 2000).

2.2.2 Layer 2: The e-learning layer

The previous section presented the main features to take into account when analysing, designing, and building of the experimentation layer. Also, a second key aspect that should be addressed is the development and/or use of a *web-based learning management system (LMS)*[1] to support the student's learning process. This platform should organize user access to the experimentation modules available and, to allow for students/teachers to interact and collaborate with each other. The implementation phase would require the following:

– Simplifying the organization of user groups.

– Offering notification services by email, instant messaging, news, etc.

– Providing all the necessary theoretical documentation such as practical guides, task protocol, instruction's manuals and any other information needed to perform a remote experimentation session.

[1] A learning management system (LMS) is a software application designed for the administration, documentation, tracking, and reporting of training programs, classroom and online events, e-learning programs, and training content.

– Guaranteeing a sequence of activities that students must carry out during an experimental session. Tasks can be of two types: 1) tasks in *simulation mode* and 2) tasks in *remote mode*. The former are the tasks that students must carry out prior to performing the experiments in the real plant. This should be done with a graphical user interface allowing students to work in a simulation mode environment, the objective being to get an adequate previous insight about the process involved. Students would then reduce time spent on activities if using the real plant. Remote access should not be allowed if the student has not satisfactorily completed previous tasks set in simulation mode. Should the student's work be evaluated positively by the teaching staff, access in remote mode would then be granted.

– Managing students and the assessment of their work as well as the uploading of reports and their tracking.

– Including an automatic booking system to schedule access to the laboratory's physical resources.

Figure 2.4 shows the structure of an e-learning platform (*e-Learning layer*) for publishing remote and virtual control laboratories (*Experimentation layer*) on the Internet.

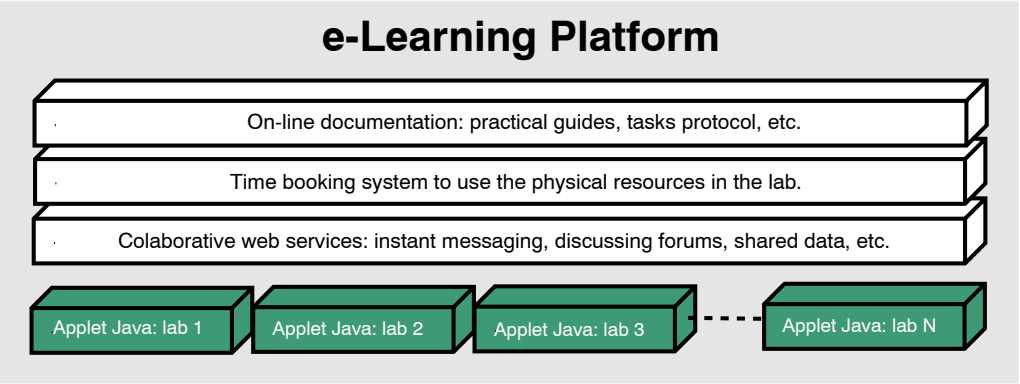

e-Learning Platform
On-line documentation: practical guides, tasks protocol, etc.
Time booking system to use the physical resources in the lab.
Colaborative web services: instant messaging, discussing forums, shared data, etc.
Applet Java: lab 1
Applet Java: lab 2
Applet Java: lab 3
Applet Java: lab N

Figure 2.4: e-learning platform architecture.

At the end of the development process, the *experimentation and e-learning layers* are integrated in order to get the final web application to publish the virtual and remote labs. Integration means performing certain links between

web modules coming from both layers, for example, to save the data collected from an experimentation Applet (*experimentation layer*) into a shared web space belonging to the *e-learning layer*. The data stored in this space could be retrieved later for analysis, or even be read again from the experimental Applet.

2.3 Conclusions

Remote and virtual control labs alone do not provide all the benefits expected. Students need to organize their work and be in contact with other users (students, teachers, tutors). This is the reason why this chapter has presented a set of requirements and specifications to apply in order to develop a remote experimentation environment for engineering education. The approach used was divided into two layers to provide a certain structure to the development process.

The planning of the global architecture of the system is a mandatory step prior to starting developing a web-based experimentation environment for educational purposes. The following chapters describe how each layer is implemented as well as the complete process used to reach the final product which is *the remote experimentation environment from the Automatic Control Laboratory of the Department of Computer Science and Automatic Control of UNED.*

Part II

IMPLEMENTATION

3

The Experimentation Layer

Overview

This chapter presents an in-depth analysis of the so-called "*Experimentation Layer*" that covers the methodology used in the design and creation of web-based control laboratories for remote experimentation.

The approach considered to create web-enabled virtual laboratories will be explained. A particular emphasis is placed on the creation of virtual-labs apply in the teaching/learning of automatic control.

Technical considerations to take into account when adding tele-operation functions to virtual-labs are also indicated. Thus, the final approach presented hereafter considers the possibility of working both in virtual and remote mode using the same graphical user interface in the client side.

Finally, a new approach to develop novel virtual and remote control laboratories using *Easy Java Simulations* and LabVIEW is presented. This framework should help developers in the creation of web-enabled environments oriented to remote diagnostics, maintenance, and experimentation.

3.1 Development of virtual laboratories

It is well known that to create a dynamic simulation of any physical system, developers must model (for instance, through a set of differencial equations) the system and then solve the equations by numerical integration methods. Software tools such as Matlab/Simulink (Matlab 2009), SysQuake (SysQuake 2009), Modelica (Modelica 2009) and others, help build virtual laboratories as they provide predefined built-in numerical methods which can be used to solve the models. By means of them, experts in different subjects can generate simulations with a certain degree of complexity to be used by teachers in classrooms with the goal of making the class more attractive and useful for their students (Kumpaty & Haeg 2007, Guzmán et al. 2008, Urquía et al. 2005, Martín 2007). However, most applications conceived with these software tools can only be used in *local mode*, i.e., the core of the simulation resides in the same machine where it is executed and therefore, these tools are not prepared to be *distributed on-line* through a communication network such as the Internet.

The natural and intuitive way to face this problem is to look for a technology that covers all aspects related to the use of simulations in *local mode* that could be distributed on-line and take advantage of the *web-based simulation technologies* available. In relation to this point, Java technology (a programming language created by Sun Microsystems) has gained enormous popularity since its launch. Some of the advantages of using Java are:

- **Java is simple**. Programming languages are not simple, but Java is considered a much simpler object-oriented programming language when compared to the programming language C++. Partially modeled after C++, Java has replaced the multiple inheritance in C++ with a simple structure called interface. The use of pointers were also eliminated.

- **Java is distributed**. Java is designed to simplify the distributed computing thanks to its integrated networking capabilities. Writing network programs in Java is like sending and receiving data to/from a file.

- **Java is portable (platform independence)**. One of the most compelling reasons to use Java is its platform independence. Java runs on most major hardware and software platforms, including Windows, Macintosh, UNIX, and Linux operating systems. Java applets are supported by Java-compatible browsers. An *applet* is a program written in Java that can be embedded in an HTML page. When a Java technology-enabled browser is used to view a page that contains an applet, the applet's code is transferred to the system and executed by the browser's Java Virtual Machine (JVM).

- **Java is multimedia (images, sounds and animation)**. The sizzle of Java is multimedia - Sounds, Images, Graphics and Video. In this growing age of multimedia, new computers are known as "multimedia ready" with CD-ROM drives, sound cards, 3D accelerator cards and other new special sound or graphic technology capabilities. Multimedia demands incredible computing power and only recently - in the past 5 years at least, affordable computers of this kind are becoming widespread.

Although one of the most relevant features is the simplicity of the language, creating a graphical simulation in Java is not a straightforward task. Conceiving relatively complex web-based applications requires advanced knowledge in object-oriented programming and other features of Java (Esquembre 2005). For this reason, the following subsection presents "Easy Java Simulations" (*Ejs* in short), the software tool used to create the virtual and remote control laboratories developed in this dissertation, and the main reasons why this tool was chosen as the development tool.

3.1.1 Easy Java Simulations as a development tool

Easy Java Simulations is a freeware, open-source tool developed in Java, specially designed to create interactive dynamic simulations (Esquembre 2005, Christian & Esquembre 2007, Ejs 2009a,b). *Ejs* was originally designed to be used by students for interactive learning purposes under the supervision of educators with a low programming level. However, the user needs to know the analytical model of the

process and the design of the graphical interface in detail. The architecture of *Ejs* derives from the *model-view-control* (MVC) paradigm, whose philosophy is that interactive simulations must be composed of three parts:

1. The ***model***, which describes the process under study in terms of,
   - Variables, which hold the different possible states of the process.
   - Relationships among these variables (laws that govern the process), expressed by computer algorithms.
2. The ***control***, which defines certain actions that a user can perform on the simulation.
3. The ***view***[1], which shows a graphical representation (either realistic or schematic) of the process and its states.

From a practical point of view, *Ejs* helps developers follow the MVC paradigm through three main sections: Introduction, Model, and View (see Figure 3.1). The *Introduction* is where the developer can write any didactical or pedagogical information related to the application (for example, instructions about how to use the simulation, exercises to complete, questionnaires, etc). *Ejs* takes all this information and transforms it into HTML pages. The *Model* covers all aspects related to the definition of the model and the control of the MVC paradigm described above. And finally, the section *View* is where the graphical representation of the virtual laboratory is built using the palette of predefined ready-to-use components of *Ejs* and where the level of interactivity is specified by modifying the internal properties of these elements.

In this sense, *Ejs* goes one step further in the process of simplifying the building of a simulation since it eliminates the "control" element of the MVC paradigm and fuses one part in the *view* and the other one in the *model*. Thus, applications are created in two steps: 1) the *model* to simulate by using the built-in simulation mechanism of *Ejs* and 2) building the *view* showing the model state and answers to the interactive changes made by users.

[1] From here on, the term *view* will be used to refer to graphical user interfaces (GUI).

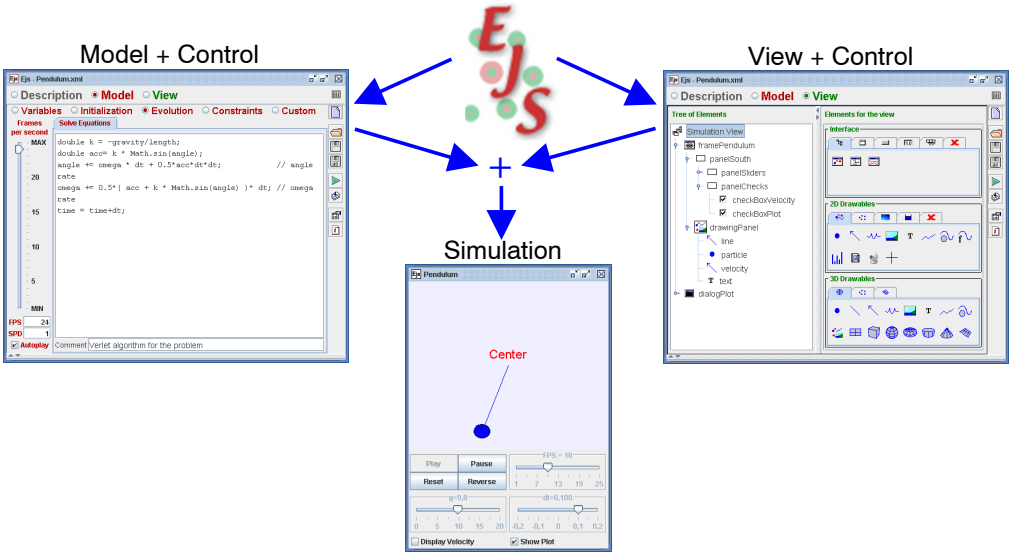


Figure 3.1: Simplified model-view-control paradigm in *Ejs*.

Ejs has been chosen in this dissertation to create the virtual-labs and the client interfaces for remote experimentation for four main reasons:

1. The tool offers a set of built-in numerical methods to solve ordinary differential equations. The chosen method is automatically called by the built-in ODEs editor to solve the models.

2. The MVC paradigm is assembled by *Ejs*. This process is hidden to users, which means they do not need advanced programming knowledge to get started with the tool.

3. The composition of complex graphical user interfaces is carried out with a simple drag-and-drop actions using predefined graphical components. Thus, *Ejs* practically eliminates the need of previous knowledge about object-oriented graphical programming.

4. New features to develop interactive simulations are continuously being added to *Ejs* (Dormido et al. 2005b, Jara et al. 2009a).

3.1.2 Structure of a generic virtual control lab in *Ejs*

Virtual-labs in the field of *control engineering education* are used by teachers and trainers to reinforce the comprehension and understanding of the control theory.

They enable students to appreciate the dynamic behaviour of a physical system when either a control algorithm or a parameter is changed. There are some guidelines to be considered in the design of virtual control labs with pedagogical perspectives:

- The complexity of the application should be considered carefully since users using the simulation (generally students from the university) will not have the on-site support of a teacher.
- Some interactive elements rich in visual contents should be included in the design of the *view* of the labs, to explain ideas, concepts, and methods present in the automatic control theory.
- A set of practical activities to complete with the virtual-lab should be prepared. Students will then be able to follow the sequence of tasks, often with an increasing difficulty, until reaching a complete insight concepts taught.

A simulation in *Ejs* will be achieved when all the information provided by developers in the description of the *model* and the *view* is assembled. Once the description is ready, then *Ejs* is enabled to generate the Java program (a standalone application or an applet) reproducing the phenomenon under study.

A general view of the *simulation's algorithm* working behind the applications created by *Ejs* can be seen in Figure 3.2. The code is divided into two stages of execution: *Initialization* and *Evolution*. The first one is devoted to the declaration of variables and the initialization code needed to describe the initial state of the system. The second one covers the algorithms that define the dynamic behaviour of the system during its evolution. Inside the *Evolution* is where both the graphical state of the system and the interactive changes from the user are carried out. Two blocks are intended for this task. In the first one, the view recovers the current values of the variables from the model and transforms them into a graphical representation (*model-view communication*). The second block is always waiting for user's interactions (*view-model communication*). The algorithms of the *Evolution* are iteratively executed while simulation is playing to get the expected result.

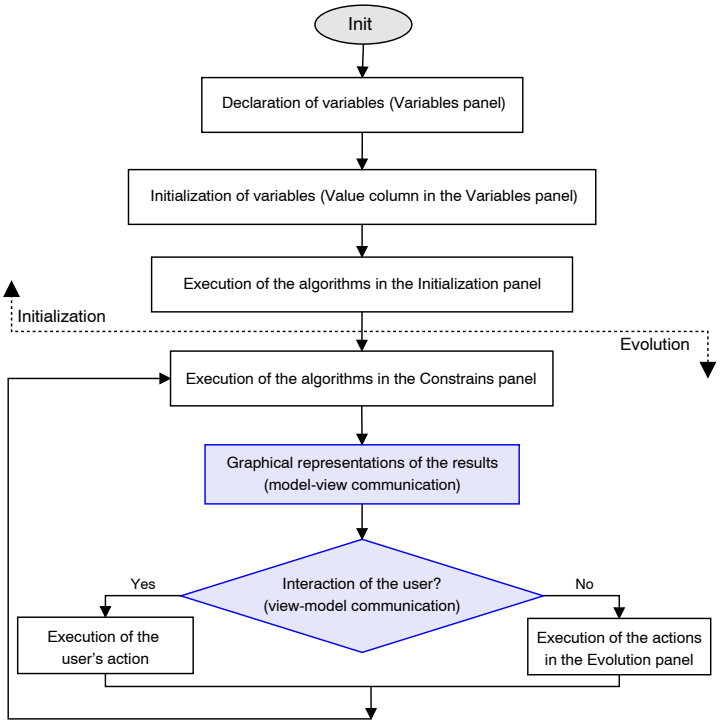
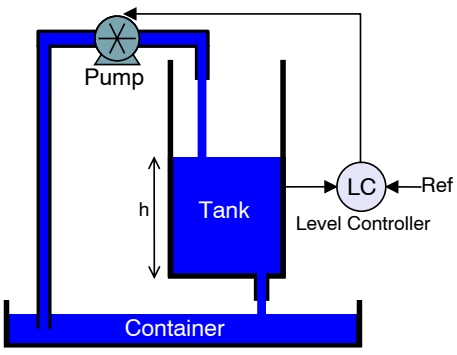


Figure 3.2: Simulation algorithm of any *Ejs* application.

To illustrate the ideas aforementioned, a simple virtual control lab of the single-tank process created by *Ejs* is introduced hereafter. The structure followed in the creation of this simple but very descriptive example will be extrapolated to the development of every study case presented in Chapter 4.

A simple virtual-control-lab in *Ejs*: The single-tank process

As mentioned in Section 3.1.1, detailed knowledge of the underlying analytical model of the process is a mandatory step before starting with *Ejs*. The creation of the virtual-lab will therefore be addressed after the model description.



Model of the Process

$$\frac{dh}{dt} = -\frac{a}{A}\sqrt{2gh} + \frac{K}{A}u$$

Variables and Parameters
$\boldsymbol{h}$: Liquid level inside the tank (m)
$\boldsymbol{a}$: Cross-section of the outlet-hole (m^2)
$\boldsymbol{A}$: Cross-section of the tank (m^2)
$\boldsymbol{g}$: Gravitational acceleration $(9.8\ m/s^2)$
$\boldsymbol{u}$: Voltage applied to the pump $(volt)$
$\boldsymbol{K}$: Pump parameter $(m^3/volt)$

Figure 3.3: Control of a first order system: The single-tank process.

Figure 3.3 shows the scheme of the single-tank process and its mathematical model. The objective is to control the liquid level inside the tank manipulating the pump that regulates the incoming liquid flow. The *level controller*, which is labelled as LC in Figure 3.3, computes its output depending on the change of the liquid level inside the tank or/and the tracking reference.

The system "*tank + pump*" can be seen as two sub-systems connected in cascade so that a simple PI control could be applied to reach the control objective. The closed-loop control scheme is appreciated in Figure 3.4.

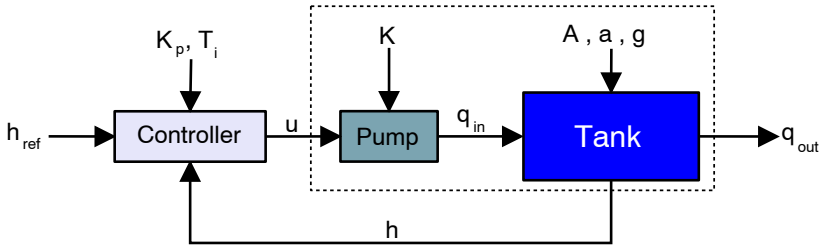


Figure 3.4: Closed-loop control in the single-tank process.

The continuous PI controller applied to the system has the form:

$$u(t) = P(t) + I(t) = K_p\, e(t) + \frac{K_p}{T_i} \int_0^t e(\tau)\, d\tau \tag{3.1}$$

$$e(t) = h(t) - h_{ref}(t) \tag{3.2}$$

For simulation with *Ejs*, the discrete counterpart of the continuous PI controller will be used. Thus, the PI controller obtained from the discretization of the continuous model is as follows:

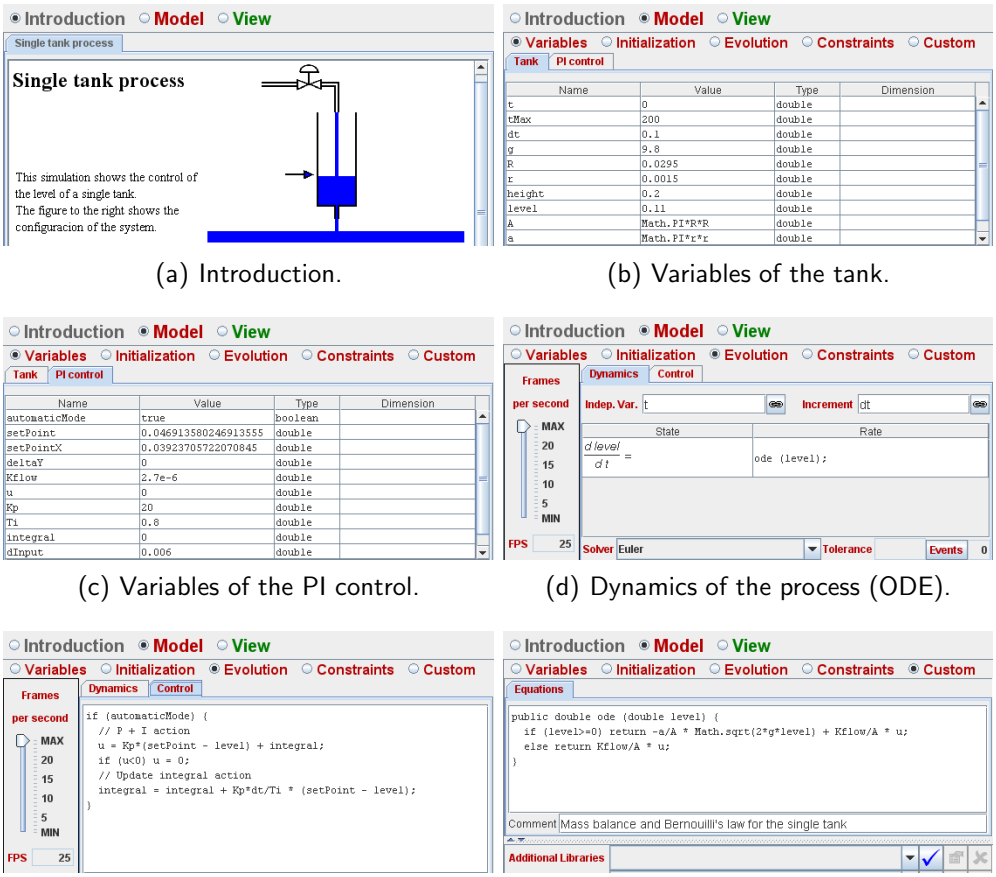
$$P(t) = K_p\, (h_{ref}(t) - h(t)) \tag{3.3}$$

$$I(t) = I(t - \Delta t) + \frac{K_p h}{T_i} (h_{ref}(t - \Delta t) - h(t - \Delta t)) \tag{3.4}$$

$$u(t) = P(t) + I(t) \tag{3.5}$$

The discrete controller includes a new variable Δt that represents the *simulation step*. This simulation step is chosen according to the dynamics of the process to satisfy the *Shannon sampling theorem* (Oppenheim et al. 1996).

The building of the virtual-lab in *Ejs* implies the definition of both the *Model* and the *View*. Figure 3.5 provides some snapshots of the *Ejs* windows to describe the *model* of the single-tank process virtual-lab.



(a) Introduction. (b) Variables of the tank.

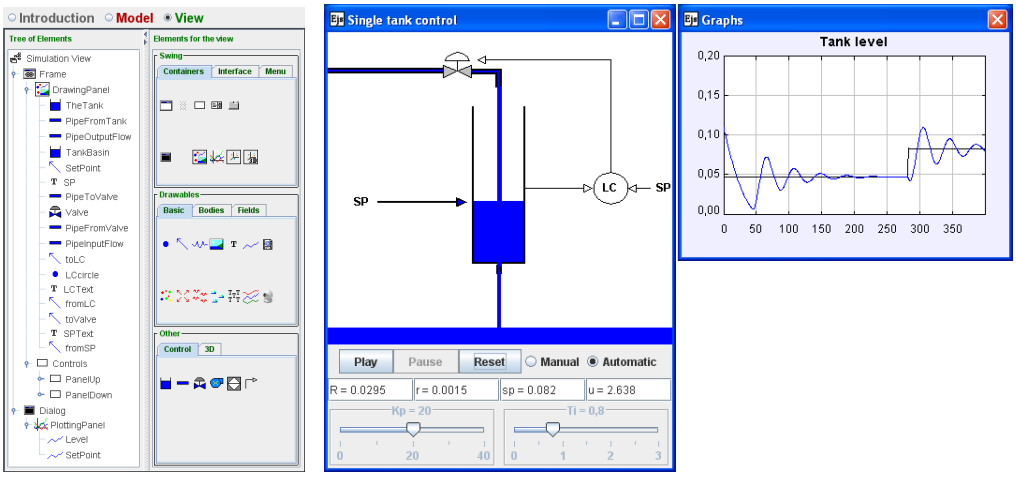
(c) Variables of the PI control. (d) Dynamics of the process (ODE).

(e) Controller. (f) The ODE as a custom method.

Figure 3.5: Defining the MODEL of the single-tank process.

In Figure 3.5(a) a brief description of the simulation and complementary information about the system can be included. *Ejs* takes this information and uses it to create HTML pages with the description on the Java applet generated. Figures 3.5(b) and 3.5(c) show, respectively, the declaration of the physical variables associated to the tank and the variables related to the PI controller. The evolution of the system is defined in Figures 3.5(d) and 3.5(e) in two pages. The first one is used to specify the mathematical model (Figure 3.3) and the second one is used to write the Java code needed to get the PI control action and the switching between manual and automatic control modes. The right side of the ODE is defined by a custom method as shown in Figure 3.5(f).

Once the model has been defined, the composition of the *view* is carried out. Figures 3.6(a) and 3.6(b) show both the tree-like structure of the *view* in *Ejs* and the final look as a standalone application of the single-tank virtual-lab.



(a) View in *Ejs*. (b) The final standalone application.

Figure 3.6: Defining the VIEW of the single-tank process.

Furthermore, the same simulation running as a Java applet embedded in a HTML page can be seen in Figure 3.7. In this sense, the advantages of using *Ejs* are obvious since the tool allows the on-line execution of virtual-labs through any Java-enabled browser.

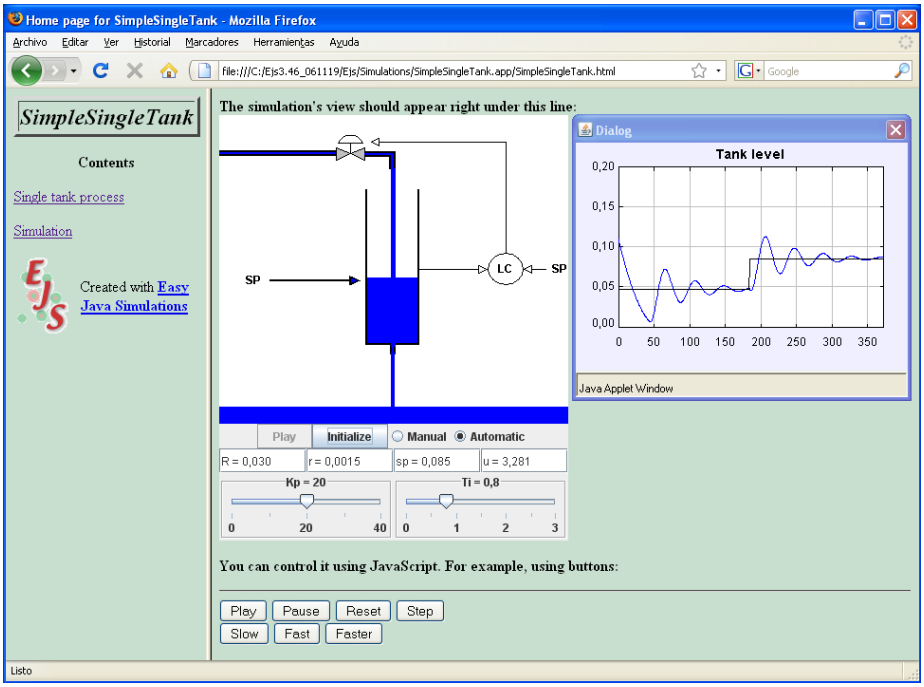


Figure 3.7: Publishing the virtual-lab of the single-tank process as an applet.

3.2 Adapting virtual-labs for remote experimentation

Virtual laboratories alone do not cover all the benefits of hands-on traditional laboratories where students can use real equipment. Moreover, it is also a fact that virtual-labs using only simulated systems can not replace working with real processes in a conventional laboratory. This means it is fundamental that virtual-labs possess tele-operation functions since the acquisition of experimental skills using real processes is of paramount importance for students of physical sciences and engineering (Garcia et al. 2008). At the same time, the design and implementation of a remote laboratory are more challenging due to safety and fault tolerant aspects which must be taken into account in its development (Casini et al. 2004).

The following sections show how the development of web-enabled control labs for remote experimentation has been addressed. A brief review of some concepts and technical considerations is offered before discussing the solutions adopted in this work.

3.2.1 Background

Carrying out the remote operation of any physical device is challenging if we take into account the amount of technical aspects that must be solved. Technical issues such as performance, interaction level, visual feedback, real-time control, user's perception, safety and fault tolerance, etc. are, in most cases, research topics by themselves (Salzmann & Gillet 2002).

In general, remote experimentation over real equipment through the Internet implies being aware of the current state of a distant system, to change the value of any input parameter of the remote system, and to perceive the effect of this change with a minimum transmission delay.

A client-server approach is commonly used to provide this functionality to virtual-labs (Callaghan et al. 2006, Zutin et al. 2008, Sánchez 2000, Salzmann et al. 2000). In particular, when a student is conducting an experiment in a

virtual manner, s/he works with an mathematical model of a process while in a remote working session relies on access to a real resource through the Internet by means of a server computer acting like a gateway.

Looking at Figure 3.8 we can appreciate what happens when a client application keeps a connection with a remote server to control a target device. The *server-side* sends in a continuous flow, the information blocks $s(k)$ representating the current state of the plant, and it receives information blocks $c(k)$ containing changes carried out by a remote user in some of the system input parameters. On the other hand, the *client-side* receives the state of the system sent by the server (contained in $s(k)$ blocks) and, at the same time, keeps waiting for some user's interaction in order to report this change to the server-side by means of new information blocks $c(k)$.

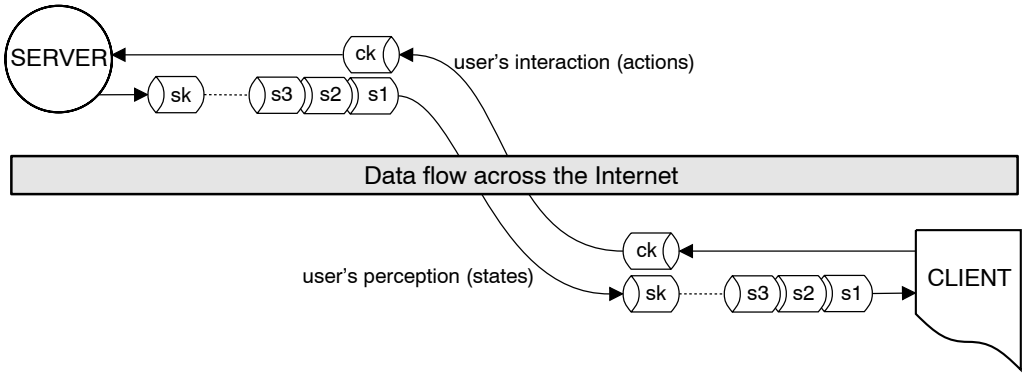
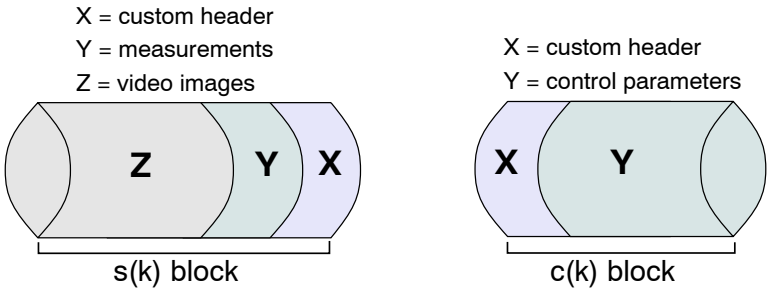


Figure 3.8: Stream of information between client and server.

Different kinds of data streams can be exchanged between client and server (see Figure 3.9). Usually, the block $s(k)$ is composed of *measurements* that represent the current state of the system (a few bytes) and *video images* (kilobytes) to provide visual feedback to the remote user. Here, it is important underline that inclusion of visual feedback is fundamental in the remote handling of a system because enhances students' motivation, their safety and the positive feeling they may experience when conducting remote experimetal sessions.

On the other hand, block $c(k)$ contains the *control parameters* susceptible to be modified by distant users. The choice of these parameters should be made in accordance with the objectives of the laboratory and the kind of experiments to run. Additionally, any other kind of information could also be transmitted in



(a) State block. (b) Control block.

Figure 3.9: Structure of exchanged data packets between client and server.

order to achieve any other specific objectives. An exhaustive study about how to modify the size of $s(k)$ packets (changing the compression factor of video images) to provide a certain level of quality of service[2] in the network communication is available in (Salzmann 2005).

To summarize, in the field of remote experimentation over the Internet the true challenge is to ensure *optimal user's perception* of the remote equipment when any *user's interaction* is carried out. Communication between client and server commonly relies on Internet protocols to transport data blocks. In this context, custom-made solutions must be addressed due to the fact that the Internet is a non-deterministic best effort network (Salzmann et al. 2000).

The following section provides some "key issues" on communication protocols used in the experimental applications developed along this work and how they have been applied seeking the best Internet practices.

3.2.1.1 Communication protocols

As described above, data packets travelling across a communication network allow a source host to reach a destination host. The data transportation is carried out using *network protocols*. Network protocols define rules and conventions to enable communication among network devices. That includes the mechanisms used to identify devices and connect them to each other, as well as formatting

[2]Quality of service (QoS in short) refers to the ability of a network to provide better service to a traffic network selected over various technologies and techniques. Elements of network performance within the scope of QoS often include availability (uptime), bandwidth (throughput), latency (delay), and error rate.

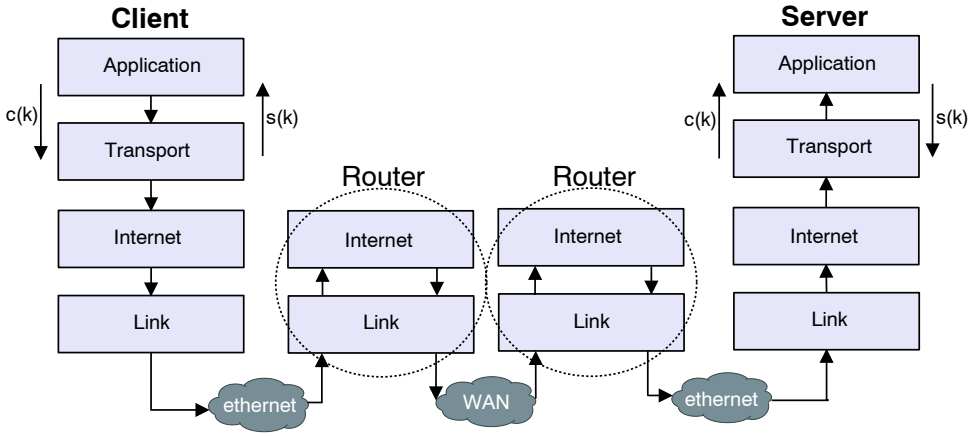


Figure 3.10: Stack connections of the Internet Protocol Suite.

rules that specify how data are packaged into messages. In the particular case of remote experimentation, *Internet Protocol Suite* is suited to encapsulate and deliver data between client and server using either the **TCP** (Transmission Control Protocol) or the **UDP** (User Datagram Protocol) protocol as transportation mechanism.

A communication scheme between two computers based on the *Internet Suite Protocols* is shown in Figure 3.10, which represents a typical scenario in remote experimentation over the Internet: a client application receiving information from a server application (*s(k)* blocks) and sending data to it (*c(k)* blocks) through the Internet. The dialogue between both hosts can be described as an *abstraction in layers* of the path followed by data from the source to the destination. The data are first generated at the *application level* and then passed down to the underling layers. Throughout this transit, the data are wrapped with the functionality provided by each layer through a new set of protocols and definitions. The number of layers depends on the network device and its functionality. For instance, in Figure 3.10, routers are represented just by two layers, *Link* and *Internet*. Effectively, routers only need the *Link layer* to connect physically to other equipments and the *Internet layer* to provide packet routing capabilities.

The IP suite is well-known to most of the researcher community and therefore, no additional information will be introduced here. More information about *IP Suite* can be found in (Dostálek & Kabelová 2006).

3.2.1.2 TCP or UDP as data transportation mechanism

User applications only see a transmission channel through the network Application Programming Interface APIs (Salzmann 2005). TCP and UDP APIs are available to user applications to communicate data. Figure 3.11 shows how data are encapsulated from the moment it is generated at the application level until leaving the host at link level. The header of a packet depends on the protocol used: TCP or UDP.

TCP is a connection-oriented service with transmission control, i.e., the destination confirms the data received and it can request a retransmission of any lost data. On the other hand, UDP is a connectionless protocol and therefore, there is no checking whether packets have arrived safely to their destination.

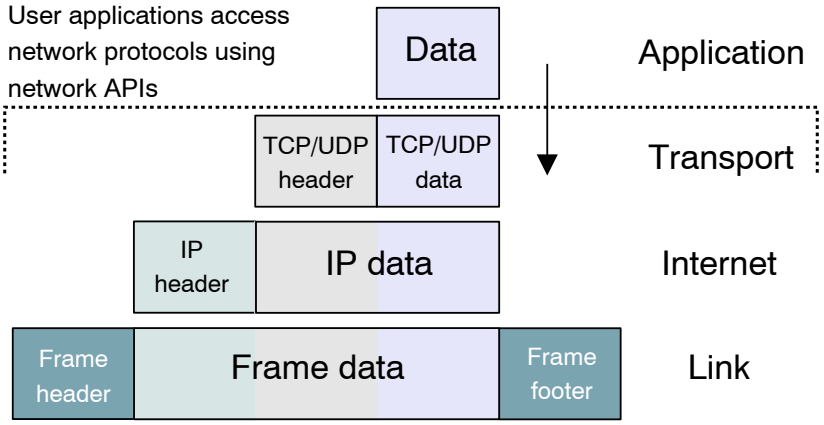


Figure 3.11: Encapsulation of data descending through the protocol stack.

From a remote experimentation point of view, we have to remember that the behaviour of the Internet is not predictable (since we have many connections occurring at the same time) and, therefore, transmission delays may occur along the transmission path. In this sense, UDP protocol is more suitable than TCP because it does not need the mechanisms used by TCP to establish and maintain connection with peers. Thus, UDP is a more lightweight protocol that does not suffer the drawbacks of TCP networks so much. Nevertheless, in this dissertation *TCP-based solutions* have been addressed, the reason being that didactical-setups used do not have dynamics that require UDP-based solutions. Furthermore, TCP is widely accepted in most communication networks and less filters in firewalls

are found for this protocol. The following sections describe in detail the structure of the terminals in a remote experimentation scheme, i.e., client and the server applications and how they use network protocols to exchange data.

3.2.2 Building the server-side

Figure 3.9 shows the content of data blocks exchanged during a peer to peer connection between client and server. Packets outgoing from the server contain data representing a semantic content different according to their origin. The generation of such information and its sending implies completing a series of tasks in the server machine concurrently. In the particular case of remote-labs, the three fundamental tasks to complete are:

1. **The control task**: It performs the real-time closed loop control of the real plant. It produces the states of the plant represented by the measurements in *s(k)* blocks (see Figure 3.9(a)). At the same time, control parameters in *c(k)* blocks (see Figure 3.9(b)) are used by the control task to modify the behaviour of the system.

2. **The video task**: It retrieves the video streaming captured by a camera focusing on the real process. Video images in *s(k)* blocks are generated by this task.

3. **The communication task**: It implements the necessary means to communicate in order to send and receive data to/from a client application. It constitutes the *s(k)* blocks and sends them to the client. At the same time, it receives the *c(k)* blocks to apply them to the system.

The more interesting task in the server-side corresponds to the *Control task* since the acquisition of signals (reading from sensors and writing to actuators) and the closed-loop control are carried out. Moreover, knowledge of *systems theory*, *control* and *real-time* must be put into practice here.

Figure 3.12 shows the standard structure of a feedback control loop. Operations performed in a feedback loop follow a standard sequence. Operations

labelled (a) and (b) in Figure 3.12 respectively represent, the measurement of the analogue output signal from the process and its conversion into digital format. Once the conversion has been completed (b), the value is compared to the setpoint value (c) to obtain the error signal. With this information the control algorithm computes the control signal (d) that is then converted to its analogue representation (e) and applied to the physical process. This sequence of operations is known as the *control task* that must be carried out at a fixed time-interval called the *sampling period* determined in accordance with the dynamics of the physical process. This fixed sampling interval or cycle time defines implementation constraints when a constant sampling period is often assumed (Åström & Hägglund 2006). The notion of real-time control is based on the above implementation constraints where computer operations rely on a deterministic time occurrence.

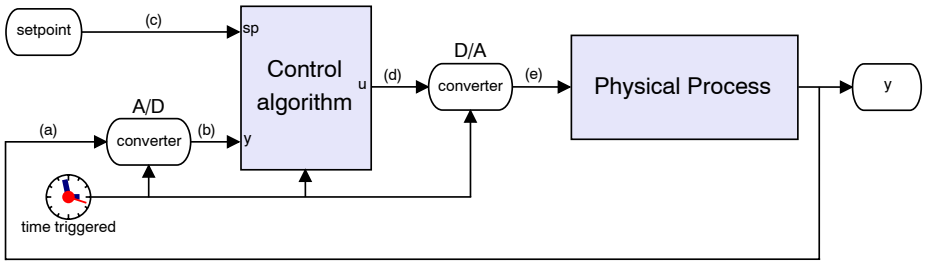


Figure 3.12: Feedback control scheme.

The development of this type of applications in control engineering education and, especially, in virtual and remote experimentation across the Internet is commonly achieved using LabVIEW software (Salzmann et al. 2000).

3.2.3 Using LabVIEW for remote experimentation

LabVIEW is a graphical programming language developed by National Instruments in 1986 (LabVIEW 2009a). LabVIEW was originally developed for data acquisition and instrumentation control. However, the lastest versions of LabVIEW allow users to use it for many other purposes: process control, industrial automation, modelling and simulation, digital signal processing, remote operation, real-time programming, etc. Programs developed with G, the graphical language of LabVIEW, are named VI (Virtual Instruments) due to their instrumentation-

related origins. A VI is made up connecting multiple blocks, from the existing libraries of blocks meant for many purposes: vision, I/O hardware, mathematical calculations, simulation, Internet protocols (Travis 2000), process control, database access, etc. One on the main reasons that encourages the use of LabVIEW is its simplicity since users with a low knowledge of programming can develop complex programs, impossible to write using traditional programming languages (Blume 2007).

Because of the hard constraints in its sampling period (reading from the sensors, execution of the control code, and writing to the actuators), the execution of the *control task* must take place as regularly as possible. With LabVIEW, such regularity is achieved by using threads and DAQ board interruptions. However, to manage a local version of the *control task* through the Internet implies some changes. For example, the LabVIEW code that handles the communication with the remote client and with the video camera that provides the visual feedback has to be included (Leva & Donida 2008). Figure 3.13 shows a general scheme of this idea.

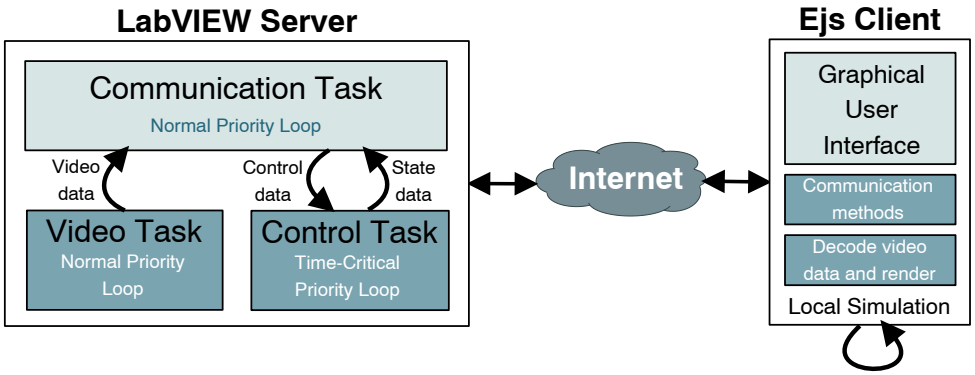


Figure 3.13: Distributed control architecture using LabVIEW and *Ejs*.

The three boxes in the server-side represent each of the tasks required. Since the control task must keep the constraints in the cycle time, the highest execution priority must be assigned to this block in order to guarantee its determinism. The *communication* and *video tasks* run in parallel to the *control task* but in different threads and with lower execution priorities. Finally, methods that share data among tasks have to be performed but must take the determinism of the *control task* into account.

LabVIEW is especially suitable here, since it provides simple multi-thread programming using *Timed Loop* blocks. These blocks allow to the programmers to include multiple threads in a single virtual instrument (VI), and running these threads at different sampling periods and with different priorities.

Figure 3.15 shows a LabVIEW block diagram that corresponds to the architecture of the server-side in Figure 3.13. The three loops in the diagram run concurrently to perform the main tasks: control, communication, and video grabbing. Figure 3.14 indicates instructions executed for each of the task.

Task 1: Control (critical time priority)

- Recover control parameters from the communication task
- Data acquisition and closed-loop control
- Transmit the system state to the communication task

Task 2: Video (normal priority)

- Get images from the camera and give them to the communication task

Task 3: Communication (normal priority)

- Receive control data from clients and write them to the control task
- Read the system state from control task and the images from video task
- Concatenate state + images and send them to the client

Figure 3.14: Concurrent tasks in the server-side.

The *control task* is a time-critical activity running at a sampling period of 20 [ms] with a priority greater than the other two threads. The *AI One PT* block reads the analogue input signal from the sensor, its output is compared to the setpoint input of the PID block and the result is fed into the *AO One PT* block that sends the resulting value to the actuator, thus completing the control task. The data structure composed of the setpoint value, the PID control parameters, the command to the actuator, and other variables is known as the *control vector*, and is sent from the *communication task* to the *control task* through *RT FIFO*[3] queues blocks (*RT FIFO* queues act as a fixed size queue, in other words the writing of data to an *RT FIFO* does not overwrite previous elements). These

[3]Real-Time FIFO queues are often used to share data among threads without breaking the determinism of their execution.

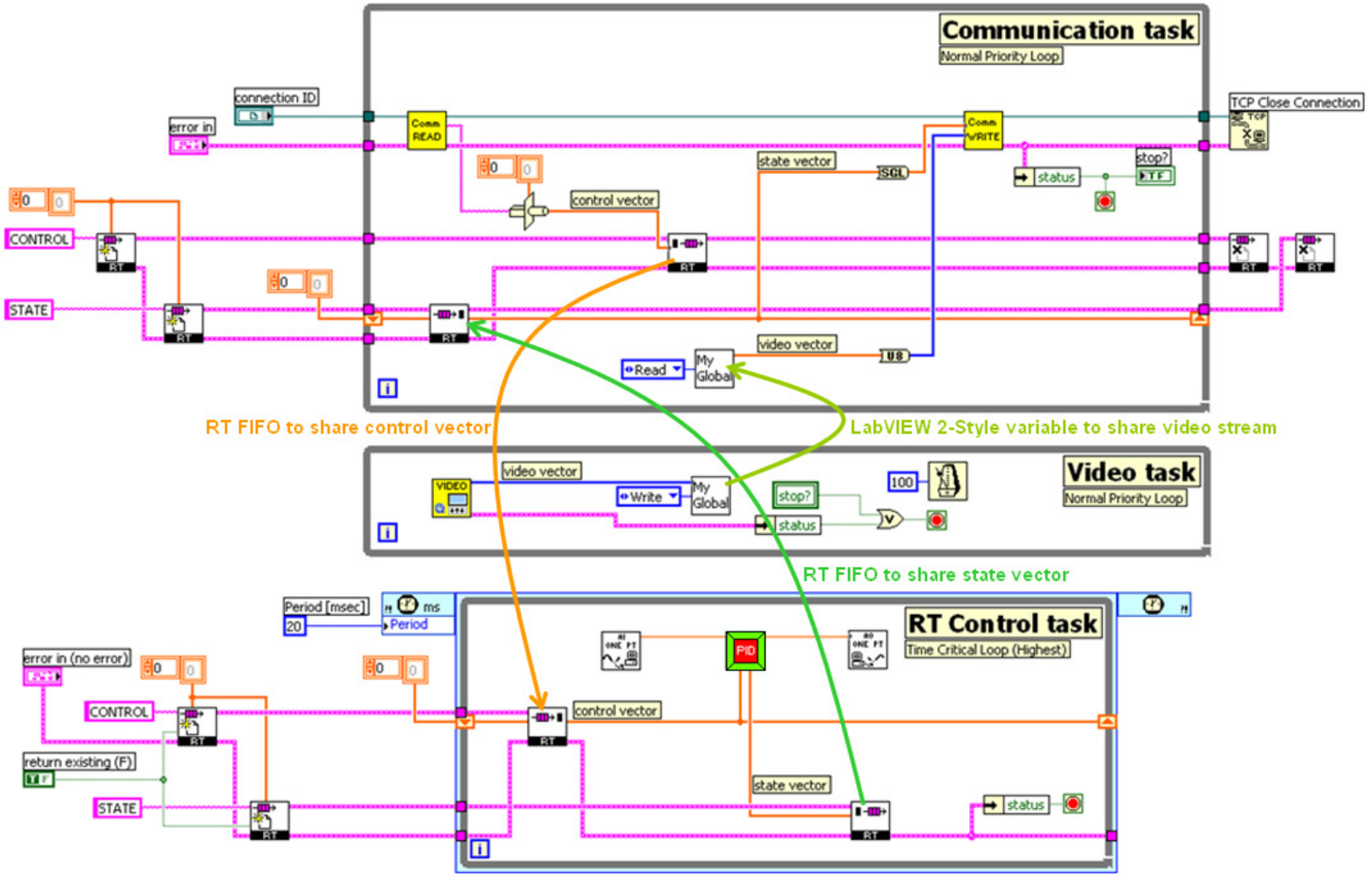


Figure 3.15: Three loops running concurrently in the LabVIEW server.

variables are produced when users interact with the client interface. The data array formed by the values sent to the actuator, the measurement from the sensor, the current time, and other variables are known as the *state vector* and is transferred from the *control task* to the *communication task* through RT FIFO queues blocks.

The *video task* is a non-time-critical activity since the loss of some video frames is generally acceptable for the user (Vargas et al. 2008). For most applications, sending five images per second is enough to obtain an adequate visual feedback of the remote system (Salzmann et al. 2000). Section 3.2.5 presents in detail how the *video task* has been implemented.

Finally, the *communication task* concatenates the current measurements (state vector) and the video frame (video vector) in a new vector. This resulting vector is sent to the client using a *Comm WRITE* block. In parallel, the control vector is received through the *Comm READ* block from the clients and passed to the *control task* by means of *RT FIFO* queues. The TCP protocol is used in both implementations because it guarantees packet delivery and bandwidth adaptation, albeit at the cost of extra transmission delays (Lim 2006, Salzmann et al. 2005). As it was mentioned in Section 3.2.1.1, a possible alternative would be the UDP protocol which provides a better control of the transmission delay. However, UDP neither has a guaranteed packet delivery mechanism nor a bandwidth adaptation mechanism, thus the designer is responsible to implement these features.

So far, the generic structure of the server-side application using LabVIEW has been presented. The client must be able to receive the information sent by the server and report changes in the control parameters. Steps linking a virtual-lab with the server-side are shown hereafter.

3.2.4 Linking a virtual-lab to the server-side

Based on experience acquired throughout of this project, the following considerations are important when *Ejs* is used to create experimentation interfaces of web-based laboratories and LabVIEW is chosen as the application running at the server side:

1. Java methods for *connecting*, *disconnecting*, *sending*, and *receiving* data blocks to and from LabVIEW server application must be created.

2. Data types in LabVIEW must match Java data types.

3. The same GUI should be used to experiment with the laboratory in either simulation or remote mode.

4. The graphical user interface must be simple and intuitive.

The methods mentioned in the first point use TCP sockets to access the communication layer. The package *java.io.net* of the Java API is used internally to support the communication.

Regarding the second point, Table 3.1 can be used as a reference for structuring the data exchanged. The selection of the data type for every variable is completed to ensure its *minimal payload*. For example, in most cases, SGL data type is sufficient to represent floating-point information instead of DBL (the payload using SGL data is the half than DBL).

Table 3.1: Casting data types LabVIEW v/s Java.

LabVIEW	Data type and payload	Value	Java
TF	Boolean (1 byte)	true or false	boolean
I32	Long signed integer (4 bytes)	-2.147.483.648 to 2.147.483.647	int
SGL	Single-precision (4 bytes)	1.40e-45 to 3.40e+38 (+ or -)	float
DBL	Double-precision (8 bytes)	4.94e-324d to 1.79e+308d (+ or -)	double
abc	String (1 byte per character)	simple text message	string
I8	Byte signed integer (1 byte)	-128 to 127	byte

With regards to the third point, a simple way to switch between simulation and remote mode must be included. Thus, when the interface is running in simulation mode, the variables associated to the system state are updated according to the evolution of a mathematical model of the process (written with the *Ejs* built-in ODE editor). However, in remote mode, these variables are true measurements.

Finally, regarding the fourth point, an interface with too many sliders, buttons, graphical elements, scopes, and auxiliary windows incorrectly distributed

would puzzle users and thus decrease their motivation (Gillet et al. 2003).

As in the server-side, concurrent tasks executing common actions must be programmed to add tele-operation features to a virtual-lab created with *Ejs*. Figure 3.16 describes these tasks and the set of instructions executed within each of them. These three tasks should be executed on independent Java threads.

Task 1: Receiver

- Get the data packets from server-side with the system state
- Decode the streams of information (video, measurements, others, etc.)

Task 2: Sender

- Assemble control parameters (input variables of the system)
- Send the control parameters to the server-side

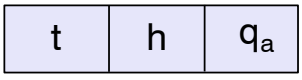
Task 3: Render

- Display the information (renderized) and detect the user interaction

Figure 3.16: Concurrent tasks in the client-side.

The virtual-lab of the single-tank process is used as an example again to explain the aforementioned ideas. Measurements by themselves can faithfully represent the dynamic behaviour of the remote equipment and, therefore, the content of this stream will be fundamental to display results on the client-side. Thus, in order to simplify the explanation provided, visual feedback is not taken into account here. Section 3.2.5 is completely devoted to explaining how this part of the development has been addressed.

The first step is to define the format of the exchanged variables in accordance with the server. Figure 3.17 shows one possible format for the data.



(a) system state.

(b) control parameters.

Figure 3.17: Structure of exchanged data packets between client and server.

The *current time* (t), *liquid level* inside the tank (h), and the *input flow* to the tank in automatic mode (q_a) constitute the states of the single-tank system (measurements). The control vector is divided into the *control mode* (m/a), the *input flow* to the tank in manual mode (q_m), the *PID parameters* (K_p, T_i and T_d), and, finally, the *setpoint* value (ref). If float data type is used to represent every variable except the control mode (boolean), the state and control vectors will respectively be 12 and 21 bytes.

In a second stage, Java methods should be programmed to control the connection with LabVIEW server. Such as Figure 3.18 shows, this implementation requieres the application of the following methods: `connect()`, `disconnect()`, `sender()`, and `receiver()`.

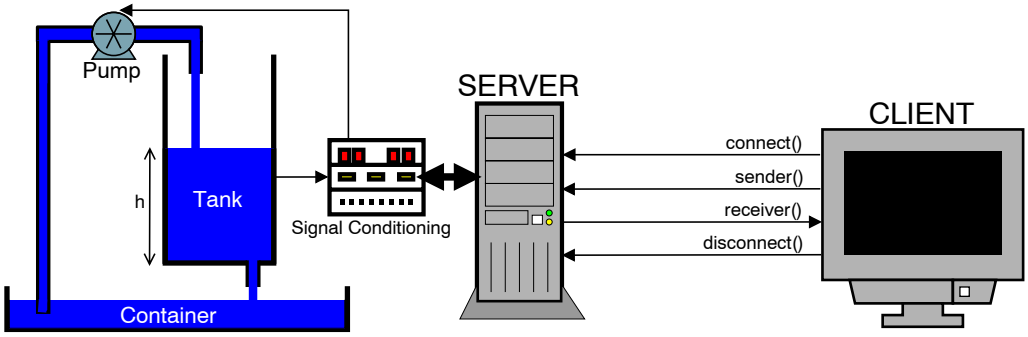


Figure 3.18: Communication methods for remote experimentation.

Listings 3.1 and 3.2 show excerpts of the Java code for establishing and releasing a connection with a server computer. TCP sockets are used to access the *network layer*. In Java, the sockets programming is done creating an object and calling to its methods. In the Listing 3.1 code, the establishing of the connection is carried out in line 5. To create an instance of a *Socket* object, the *domain name* (or IP address) and the *service port* in the remote server are required by the constructor. Then, in lines 6 and 7, the input and output stream buffers are created. These buffers act as FIFO storing queues whose filling and emptying depend on possible delays in the network communication. The disconnection from server-side is made by invoking the `close()` method in the socket and the input/output stream buffers (lines 6, 7, 8 in Listing 3.2).

Listing 3.1: Excerpt of the Java code to connect the *Ejs* client to server side.

```
public boolean connect(){

  connected = false;
  try {
    javaSocket = new Socket("onetank.dia.uned.es",2055);// create connection
    in = new DataInputStream(javaSocket.getInputStream());// input buffer
    out = new DataOutputStream(javaSocket.getOutputStream());// output buffer
    if (javaSocket != null) { // If connected ?
      connected = true; // connection is ok ...
      _play(); // executing evolution
    }
  }catch (java.net.IOException io) {
    System.out.println("Method startTCP: Problems connecting to host.");
  }
  return connected;

}
```

Listing 3.2: Excerpt of the Java code to disconnect the *Ejs* client from server side.

```
public void disconnect(){

  if (connected) {
    if (javaSocket != null){
      try {
        in.close();// close input stream
        out.close();// close output stream
        javaSocket.close();// close connection
        javaSocket = null;
        in = null;
        out = null;
        connected = false;
      }catch (java.io.IOException e){
        System.out.println("Method closeTCP: Close socket error.");
      }
    }
  }

}
```

The `receiver()` and `sender()` methods (see Listings 3.3 and 3.4) should be launched on independent Java threads just when the `connect()` method is started. The `sender()` method is used to report changes in the view that affect the operation of the remote equipment. The `receiver()` method recovers the incoming data sent from the LabVIEW server.

These methods are integrated into the definition of the *Model* and *View* of the virtual-lab of the single-tank process in *Ejs*. Once the methods have been added to *Ejs*, the programming logic that discriminates between working on simulation or remote mode is created. The updating of the variables in simulation is carried out based on the evolution of the mathematical model or in the case of remote mode, on real measurements obtained from the server.

Listing 3.3: Java code at the client side to receive data from the server side.

```
public void receiver(){

  if (connected) {
    try {
      time = in.readFloat();//read time from server
      level = in.readFloat();// read level from server
      qautomatic = in.readFloat();// read input flow from server
    }catch (java.io.IOException e) {
      System.out.println("Method receiver: Error receiving data.");
    }
  }

}
```

Listing 3.4: Java code at the client side to send data to the server side.

```
public void sender(){

  if (connected) {
    try {
      out.writeBoolean(m/a);//write control mode
      out.writeFloat(qmanual);//write input flow in manual
      out.writeFloat(Kp);//write proportional gain
      out.writeFloat(Ti);//write integral gain
      out.writeFloat(Td);//write derivative gain
      out.writeFloat(ref);//write setpoint
      out.flush();// flush data to client
    }catch (java.io.IOException e) {
      System.out.println("Method sender: Error sending data.");
    }
  }

}
```

The data are also rendered to the client by an *Ejs* view. The interface contains the same graphical elements of the virtual-lab but now the dynamic behaviour of the elements is updated using the measurements obtained from the server when working in remote mode.

The previous lines provide guidelines and a background to convert a virtual-lab created by *Ejs* into a remote/virtual lab. However, the development of applications using these approaches implies implementing a specific software on the server-side (LabVIEW) and on the client-side (*Ejs*) and, therefore, new applications for remote experimentation will need to implement all the tasks described on both sides.

Nevertheless, the thesis has addressed one way to take advantage of the legacy code concept and present a new framework for developing virtual and remote labs. Section 3.3 will present the new approach that covers this objective.

3.2.5 Visual feedback from the remote plant

A remote visualization system is an essential element in any tele-operated environment since it allows the users to feel and be aware of the consequences of their actions during a remote working session. As a result of this, users are more motivated and confident in the use of the system.

In order to include this module in the construction of the *Ejs view*, two alternatives were tested. The first one considers the use of an IP camera with a built-in video server dedicated to capturing images and post-publishing them as video streaming through its network interface (see Figure 3.19, option 1) while the second alternative considers using a conventional webcam with serial interface (RS-232 or USB) directly connected to the server computer (where the server computer could be the same host that controls the real plant). The publishing of the video stream is not direct in this case since the image data must be acquired via webcam through its serial interface first and then socket techniques should be used to send these data together to the plant state data across the network (see Figure 3.19, option 2).

Most of the remote laboratories created during the development of the thesis project work with the first alternative suggested. It was chosen for its low

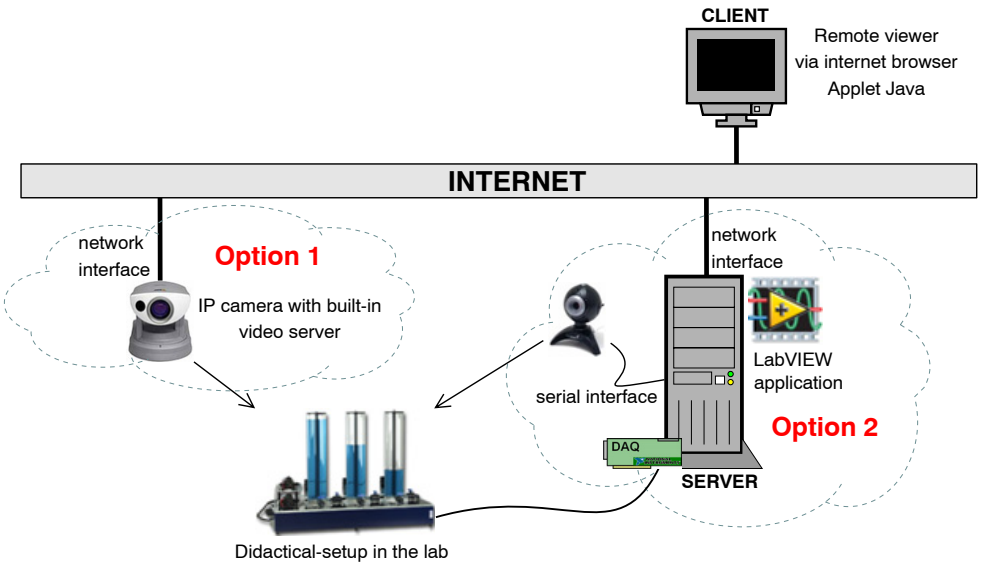


Figure 3.19: Visual feedback of the remote plant through video images.

maintenance, the fact that it is easy to use and, mainly because it is possible to control the zoom and vision angle of the mechanism by means of HTTP requests programmed at the client side. Figure 3.20 shows the camera SONY EVI-D31 used to display video images in the virtual and remote control laboratory of the three-tank system presented in the following sections of this chapter. Although most existing IP cameras in the market are all-in-one solutions, that is, camera and video server, in this case, the hardware to capture video images (the camera itself) is connected to an external video server able to deploy the frames through its network interface to the users. Video server and camera are connected using their serial ports.

Figure 3.20: Camera SONY EVI-D31 with external video server AXIS 2400.

The external video server AXIS 2400 allows to connect up to four cameras which can be used independently. Furthermore, the AXIS video server is prepared so as to receive incoming command from clients to make specific functions on the camera. It allows, for example, to change the zoom view, to move the camera, to switch between cameras connected to the server, etc. All these functions can be performed from a remote graphical user interface by means of HTTP requests.

The second alternative to obtain visual feedback from the remote process is a low cost option. The main drawback of this approach is that it requires a higher programming effort since it is necessary to create a software to acquire the images and publish them on the Internet. However, it allows for a better control of the video streaming. For example, in (Salzmann 2005), the author works using this option to implement algorithms capable of adapting the quality of the images received (by modifying a compression factor) by the client according to changes in the quality of service in the network communication.

3.2.5.1 Development of the Java library *webcam.jar*

In order to read the video streaming published by the video server of an IP camera, a Java library, called *webcam.jar*, was developed. This API allows Java programmers to use the classes and methods of the library to get video images from any IP camera connected to the Internet. The software provides a first level of interface with the camera, allowing to write high level software hiding the low level programming details such as the structure of the received packets, the decoding of the HTTP headers, or the sockets implementation.

The main class of the API, called *Video.class*, includes a constructor that allows to create an instance of a *Video* object with the following input arguments: a *string* indicating the URL where the camera supplies the video stream, a *boolean* indicating what the reading format either (MPEG[4] (true) or JPEG[5] (false)) and, finally, an *integer* to include a delay (in milliseconds) in the reading of the images. A detailed description of this class and its methods is provided below:

`public Video(String url, boolean isMPEG, int delay):`

When an object of this class is created, a *Java thread* is ready to be started. Once launched, the set of public methods that the *Video* class provides can be used to control the connection with the camera. These methods are:

`public start();`

This is the main method of a *Video* class. When the `start()` method is invoked on a *Video* object previously created, the `run()` method of a *Java thread* is executed. The `run()` method of *Video.class* opens a socket connection to the remote IP camera and it starts the reading of the video stream according to the chosen format.

`public closeStream();`

This method stops reading the video stream and closes the socket

[4]The Moving Picture Experts Group, commonly referred to as simply MPEG, is a working group of ISO/IEC charged with the development of video and audio encoding standards.

[5]In computing, JPEG is a commonly used method of compression for photographic images. The degree of compression can be adjusted, allowing a selectable tradeoff between storage size and image quality. JPEG typically achieves 10 to 1 compression ratio with little perceivable loss in the image quality.

objects created at low level. The `run()` method of the thread is over when this method is executed.

`public boolean isConnectedVideo();`

Enquires if the link to the camera is up or down. Commonly, this boolean indicator is used when the `getImage()` is invoked to get the images.

`public Image getImage();`

The images captured from the IP camera can be obtained from the input buffer by using this method. The method returns an object of the *java.awt.Image* class. Image objects are easily displayed on *Java swing*[6] *components*.

Summarizing, Java programmers can import this library to capture the streaming video of any IP camera connected to the network. With regards to the present essay, the library was developed in such away that its inclusion in the development process of a new virtual and remote laboratory can be achieved with a minimum programming effort. Following this philosophy, the library *webcam.jar* was integrated into *Ejs* as a new view element. Then section presents this new component and how it can be used by *Ejs* users.

3.2.5.2 The *WebCamImage* view element in *Ejs*

In order to simplify the use of the *webcam.jar* library, a new view element of *Ejs* called **WebCamImage** was developed. The novelty of this approach lies in that the element was implemented based on the characteristics of an existing graphical component of *Ejs*, the **InteractiveImage**. Thus, the *WebCamImage* element inherits all methods and properties of this last object and, can therefore, be placed on an *Ejs* container with coordinate axis such as the **DrawingPanels** or the **PlottingPanels** in order to render the images from the camera.

Figure 3.21 shows how to use the *WebCamImage* element in an *Ejs* appli-

[6]Swing is a widget toolkit for Java. It is part of Sun Microsystems' Java Foundation Classes (JFC) - an API able to provide a graphical user interface (GUI) for Java programs. Swing was developed to provide a more sophisticated set of GUI components than the earlier Abstract Window Toolkit.

cation. Here, we can see that, in addition to the properties inhereted from the *InteractiveImage* element, three new parameters must be configured. These parameters are related to the IP camera used since a *Video* object from the *webcam.jar* library is created. In the example illustrated in Figure 3.21, the value of these parameters are:

```
URL=http://IP_ADDRESS/axis-cgi/mjpg/video.cgi
MJPEG=true
delay=20
```

where URL is the http location provided by the video server AXIS 2400 to access the stream MPEG, MJPEG is the reading format (TRUE in this case), and the delay between the reading of two images was set to 20 [ms].

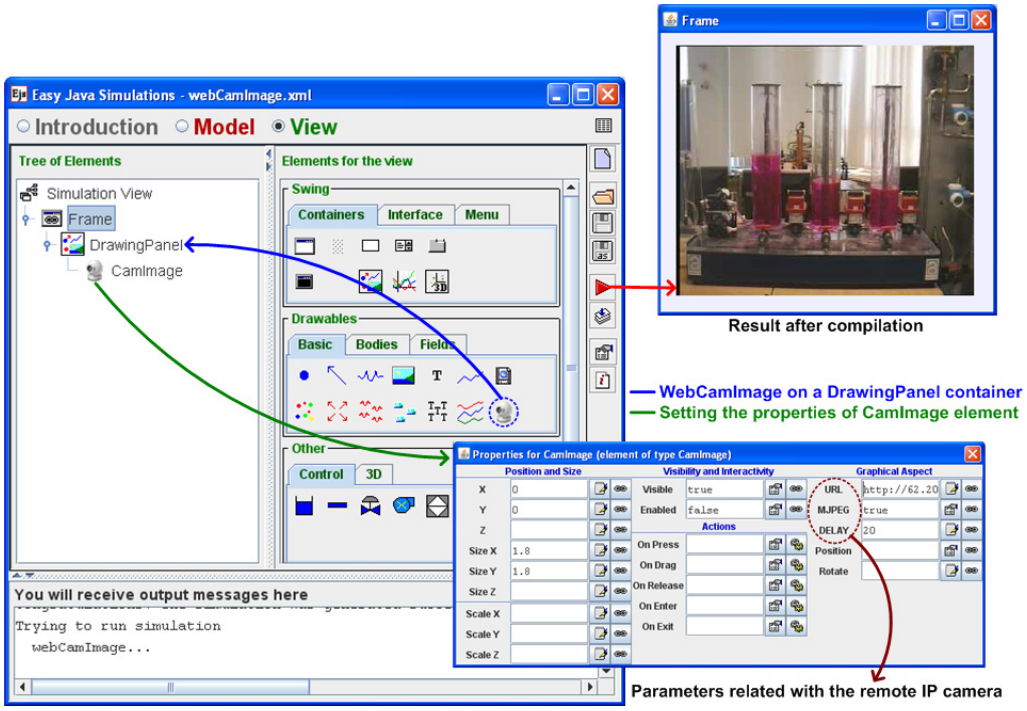


Figure 3.21: WebCamImage view element on *Ejs*.

➠ **Remarks**: The MPEG format is not available in all IP cameras. Should this be the case, the JPEG format could always be used. The JPEG format recovers single images from a remote camera through http requests whereas the MPEG format gets the images compressed as a raw flow of bytes.

3.2.5.3 The *Augmented Reality* concept

The *augmented reality* concept in remote experimentation tries to give an added value to the remote visualization module **WebCamImage** by overlaying the simulation view (created using the set of graphical elements of *Ejs*) over the video images.

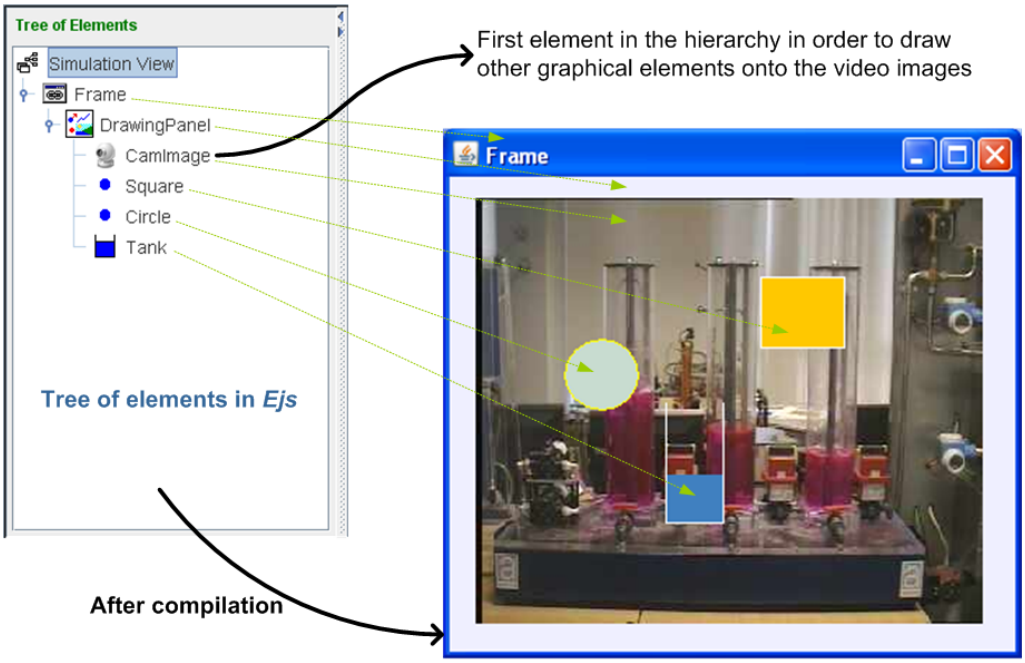


Figure 3.22: Simple illustration of the *augmented reality* concept.

Figure 3.22 depicts the idea previously described. From a practical point of view, the development of this point has already been explained in Section 3.2.5.2, since its conception is strongly inspired by the **WebCamImage** element. This component was built in such a way that it can be added onto *Ejs* drawing containers with coordinate axes (such as **DrawingPanels** or **PlottingPanels**). Consequently, this effect is achieved when adding a **WebCamImage** element as a first object of a drawing container of *Ejs*, since the captured images will always appear in the background, behind the other graphical elements.

The direct application of the augmented reality concept and its benefits in remote experimentation will be shown in the prototypes of web-based control labs presented in the following chapter.

3.3 A new approach to connect Java and LabVIEW

3.3.1 Motivations

The deployment of web-based control environments is beneficial both for final users and developers (process control engineers and teaching staff). However, developers face the extra work required to transform an existing local system into a web-based environment. Developers know how to manage the hardware and the software in a local control system well, but new problems arise when making the system accessible through the Internet. Specifically, an interactive graphical user interface for the system must be set up such that can be deployed through the Internet in the form of a Java applet. Java applets are the simplest way to integrate interactive user interfaces for remote supervision into web-based learning management systems. Examples of this use of Java are eMersion (Gillet et al. 2003), PIDstop (Eikaas et al. 2006), and Java-based SCADA systems (Fan et al. 2005). Let's consider the case of a virtual instrument (VI) program created with LabVIEW. Publishing a LabVIEW VI on the Internet is a long-familiar, click-and-share feature of this software (Shirer 2001, Nitu et al. 2005, Adamo et al. 2007). However, there is no simple mechanism to make the VI variables (controls and indicators) accessible for Java applets. Making the VI and Java communicate across the Internet requires modifying the VI's wiring diagram to include additional LabVIEW TCP/IP blocks. This requirement poses an important setback for developers who want to transform existing LabVIEW-based local control systems into web-based ones.

The following sections present an alternative approach, and a very promising one, for the quick and simple creation of web-enabled control environments which use LabVIEW on the local side, Java applets on the remote client, and TCP/IP as the communication channel between both elements. The solution is based on:

- A stand-alone application, called JiL (Java-internet-LabVIEW) server, which acts as middleware to publish an existing LabVIEW VI on the Internet, and

– A Java library file which Java clients can use to control and access the variables of the JiL-published VI.

The novelty of this approach is that the controls and indicators of the VI can be accessed from the Java program by the LabVIEW developer in a fully transparent way, that is, without introducing any modification to the original VI. Outcomes of this research have been disseminated in (Vargas et al. 2009a).

3.3.2 Technical issues of the JiL Server middleware layer

The built-in local communication facilities of LabVIEW allow to include communication facilities at design time with almost any existing software and hardware (via DLLs, Active X, .NET, TCP/IP, Ethernet, Bluetooth, CAN, OPC, IEEE 1394, RS232/485, GPIB, etc.) as well as with other scientific packages such as Matlab/Simulink or Mathematica. However, once a LabVIEW VI has been developed, implementing a bidirectional data exchange with a Java applet requires editing the existing VI wiring diagram to include new TCP/IP communication blocks into the diagram. It also requires implementing the TCP/IP-based communication library calls in the Java client. This procedure is time-consuming and requires both knowledge of Java and an understanding of how TCP/IP communication works. But also, maintainability and scalability of legacy code is compromised since the author of the original code is not always available to carry out these modifications.

Web-enabled environments for remote diagnostic, control, or experimentation are commonly based on client-server architectures where TCP/IP links are used to exchange data and commands between both sides. Figure 3.23 depicts the design pattern known as *command-based architecture* (LabVIEW 2009b) that is the base of the JiL approach. Command based architecture is focused on high-performance applications where both the minimization of the network traffic and the ability to manipulate different data types using a naming convention to the variables represent the fundamental objective. The communication protocol covers the following characteristics:

- To minimize network traffic by sending data only when needed.
- To set and get parameters with different data types from the client side through the use of variable names hiding the TCP implementation details.
- To send metadata information to ease the data packaging and parsing.

To decrease the delays caused by the communication network and make better use the bandwidth, the exchange data between client and server is done asynchronously. This "key idea" is based on the fact that users do not interact with the application continuously. For this reason, communication between client and server is unidirectional in every step of evolution (the server sends the state of the process to the client), being bidirectional only when users interact with the graphical interface (the client sends input variables only when the user makes an interaction over the simulation).

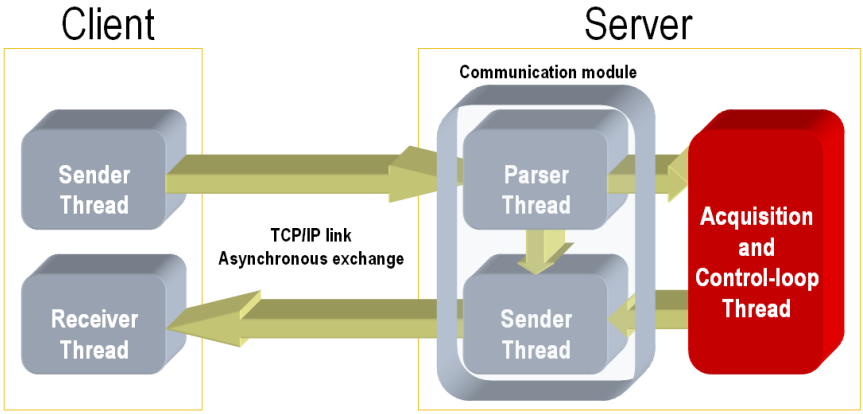


Figure 3.23: Command based architecture.

As Figure 3.23 shows, the server side performs three tasks: the *Command Parser*, the *Sender*, and the *Control Loop*. The Command Parser receives commands from the client, interprets them, and executes actions requested. When no request is received, the Command Parser remains in sleeping mode, leaving the processor free for other duties. Similarly, the Sender "sends" the measurements acquired by the Control Loop to the client side when required by a command.

Analyzing the server side of Figure 3.23, it is clear that a separation line can be drawn between the two communication tasks (gray boxes) and the Control Loop (red box), which is the task connected to an industrial process or didactical

setup. In this scenario, the Control Loop is a LabVIEW VI able to supervise, diagnose or control actions, in principle with no TCP/IP communication capabilities. To provide a convenient TCP/IP wrapping to the Control Loop, the JiL server is introduced in the scheme. This middleware plays the role of both the Command Parser and Sender blocks of Figure 3.23 and communicates the Control Loop VI with a remote Java client in an effective manner.

To publish a VI using the JiL server, the author first starts the JiL server program and uses its control panel (the File menu of Figure 3.24) to select the local VI to be published. Pressing the "Start" button finishes the publishing task. Every control and indicator of the VI becomes immediately accessible to any applet that uses the provided Java library file (see next subsection).

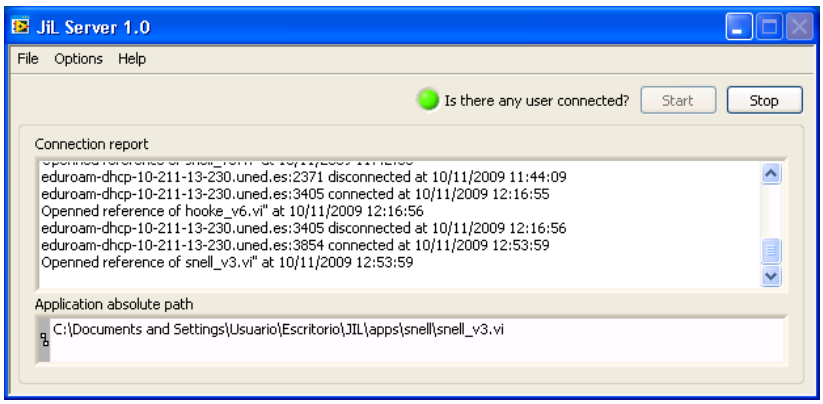


Figure 3.24: The JiL Server front panel.

When a VI is published through the JiL server, the server performs an automatic scan of all the VI controls and indicators, initializes the network input port, and waits for an incoming connection from a Java applet. When the connection is established, the server then listens for incoming commands which it parses and serves as requested. More details about this process can be found in (JiL 2009).

There are three types of commands: request, control, and state commands. Request commands require information about the controls and indicators available, which the server returns in the form of a list. Control commands are used to open, run, stop, or close the VI. These commands perform the same function as if a user interacts with the VI locally. Finally, state commands are used to read the value of an indicator or set the value of a control in the VI.

3.3.3 Details of the JiL Server implementation

The JiL server was developed in LabVIEW, making use of its **VI Server** feature. The VI Server is a collection of functions that allows to access objects and functionalities of a virtual instrument programmatically (Travis 2000). Any VI exposes properties and methods. These can be accessed through block diagram functions. A property is a characteristic of a virtual instrument that may be either read and/or written, depending on the property. An example of a virtual instrument class property is *Execution:State* which indicates the execution state of a VI (bad, idle, and running are possible values of this property). A method is an action that is performed on a virtual instrument. For example, the *Run VI* method is used to run programmatically a VI in the same way as pressing the run button in the VI's user interface manually. Figure 3.25 shows a template of how LabVIEW Invoke Node blocks are used to execute methods and set or get property values.

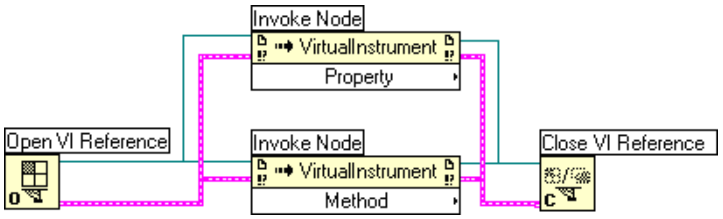


Figure 3.25: Use of two Invoke Node blocks to modify a property and invoke a method on a virtual instrument.

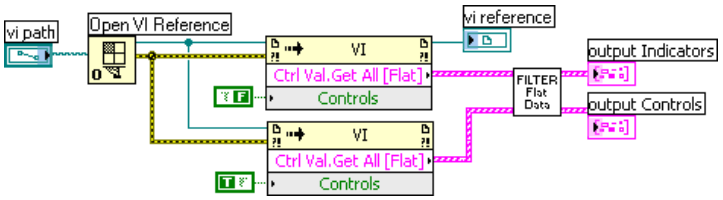


Figure 3.26: Part of the JiL Server wiring diagram that obtains the list of a VI controls and indicators using two Invoke Node blocks.

When a LabVIEW virtual instrument is published through the JiL server, the server's first action is a programmatic reading of all VI controls' and indicators' names using the method *Control Value: Get All* in two Invoke Nodes blocks (see Figure 3.26). It does this by calling the `control-value-get-all` method in two invoke-node blocks, one to get the indicators' names and the other for

the controls' names. Once the JIL server receives this information, it awaits an incoming connection from a Java applet. Once the connection is established, the server continues to listen for incoming commands from the applet.

Anytime the JIL server receives a command, it is parsed and processed according to its type. If the command is a request for the controls and indicators available, the JIL server returns the name list (as it was extracted when the two invoke blocks obtained it). When the user issues a control command, s/he can start, stop, or reinitialize the VI via invoke nodes with `run-VI`, `abort-VI`, or `reinitialize-all-to-default` methods. The server can receive a state command, which is either to read an indicator or to write a control. Either way, the corresponding method performs this action in an invoke-node block. The rest of the time, when information is not received, the JIL server is on waiting mode.

3.3.4 API Java to control LabVIEW applications

Applying Figure 3.23 to this scheme, a JiL-enabled Java client must implement two (*Sender* and *Receiver*) communication tasks to interact with the published VI. The Sender task is to send control commands or state commands to set the values of VI controls whenever the user interacts with the client's user interface. The Receiver task periodically reads the values of VI indicators sent from the Sender of the JiL server. For example, in a web-enabled control application, values sent from the Java client can be controller parameters and commands to *start/stop* the feedback control loop, and the data stream received back will contain data on the state of the process (the level of a tank, the temperature in a heat-exchanger, the angular position of a motor, etc.).

These communication tasks can be easily implemented in a Java program by using the methods provided in a utility class called *Jil.class* in the package called *jil*. Tables 3.2 and 3.3 list the methods provided by *Jil* main class.

The first method to invoke on a *Jil* object is the `connect()` method, which establishes the connection with the server. Then, `openVI()` is used to open a remote VI and report the list of control and indicators of the remote VI to be exchanged. This internal list acts as a buffer to improve the communication performance.

This means that, by reporting the format of variables to exchange, both client and server know beforehand what variables will be sent and received during connection. Thus, when `run()` method is invoked, a private method (called from *Receiver* thread of the *Jil* class) reads all the values from the JiL server into the internal list and places them in a buffer, from which the `getValue()` method retrieves their values. Similarly, to modify the value of one or more VI controls, the suitable `setValue()` methods must first be called to set the new values in a buffer. This buffer is read by a private method (called from *Sender* thread of the *Jil* class) which, when all values have been set, transmits the new values to the JiL Server.

Table 3.2: API Java of the Jil class (methods to control the connection).

VI Control Methods of the API
`Jil(String serverAddress)`: Constructor used to create a JiL object.
`void connect()`: Creates and initializes the TCP/IP connection with the JiL server.
`void disconnect()`: Closes the TCP link with the JiL server.
`boolean openVI(String modelPath, String initCmd)`: Opens a VI specified by modelPath and reports the exchange variables by initCmd.
`void closeVI()`: Closes a refnum associated with an openned VI.
`void run()`: Starts the VI. A java.io.IOException is thrown if an I/O error occurs.
`void stop()`: Stops the VI. A java.io.IOException is thrown if an I/O error occurs.

Table 3.3: API Java of the Jil class (setter and getter methods).

Setter and Getter Methods of the API
`setValue(String name, boolean value)`: Sets a BOOL variable to LabVIEW.
`setValue(String name, int value)`: Sets a I32 variable to LabVIEW.
`setValue(String name, float value)`: Sets a SGL variable to LabVIEW.
`setValue(String name, double value)`: Sets a DBL variable to LabVIEW.
`setValue(String name, String value)`: Sets a STR variable to LabVIEW.
`boolean getBoolean(String name)`: Gets the boolean value from LabVIEW.
`int getInt(String name)`: Gets the integer value from LabVIEW.
`float getFloat(String name)`: Gets the float value from LabVIEW.
`double getDouble(String name)`: Gets the double value from LabVIEW.
`String getString(String name)`: Gets the string value from LabVIEW.

Figure 3.27 summarizes the JiL Server approach within the overall infrastructure. The framework relies on the use of two software tools particularly useful to develop the *experimentation layer*: LabVIEW and *Ejs*. The approach is based on the creation of generic communication modules both on the client and the server sides. On the client-side, the Java library *jil.jar* was created. By this API, the TCP protocol is hidden to users and instead, simpler Java classes/methods

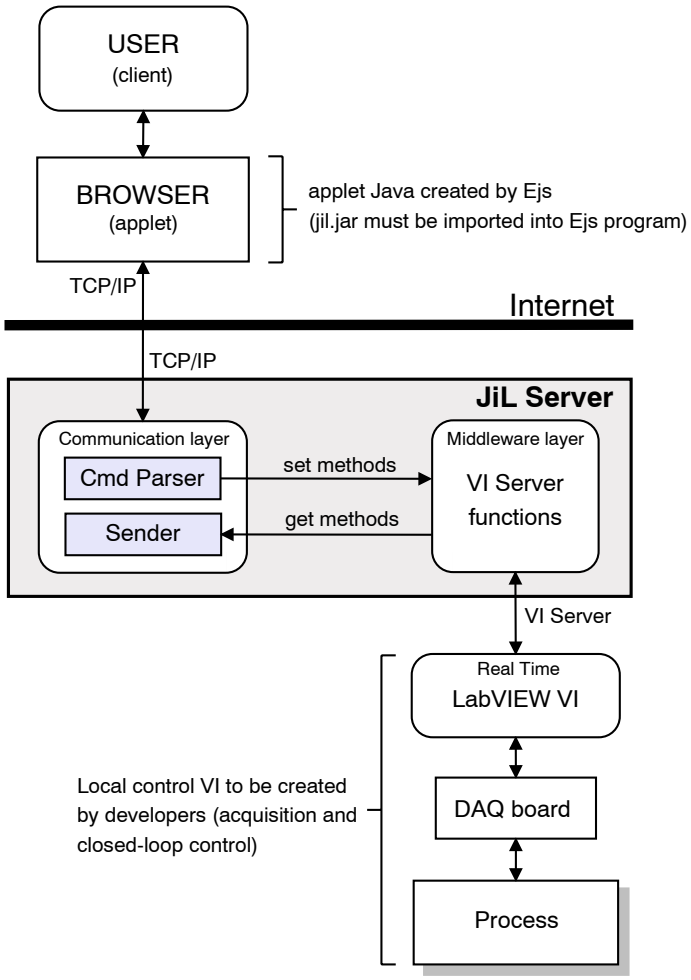


Figure 3.27: Modular view of the JiL Server approach.

used to set up the connections are provided. This library can be easily integrated into *Ejs* programs to dialog with the server. Similarly, on the server-side, the LabVIEW executable program *JiLServer.exe* operates as a middleware communication layer between the client and the process. Thus, developers are only required to create a local control VI that performs the acquisition and closed-loop control of the plant.

3.3.5 A very simple example of use

Now, a complete, albeit rather naive example is presented to describe the library. Consider the flat sequence structure of a generic VI for feedback control of an industrial process as shown in Figure 3.28.

In this structure, an initial frame, labelled “Init HW” is used for hardware

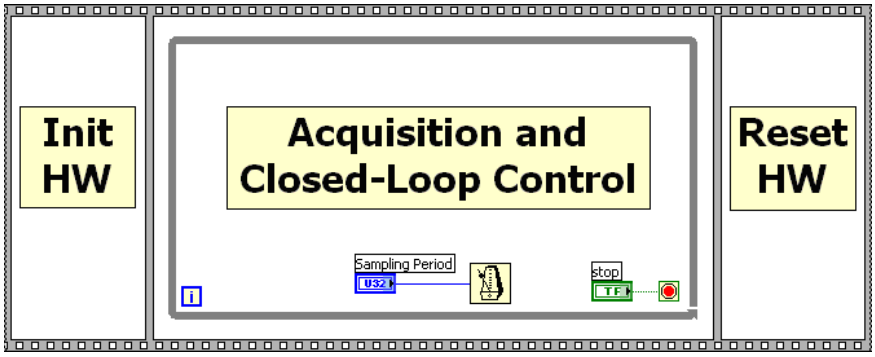


Figure 3.28: Scheme of a generic VI for feedback control purposes.

initialization code and a final frame "Reset HW" is used to leave the process in safety conditions when the control operation is finished. The central Control Loop wiring diagram of the VI must be designed according to purposes sought (control, supervision, diagnostics, identification, etc.). It could, for instance, implement a timed loop with the control code (such as a PID controller). The VI scheme of this central diagram used for this example is presented in Figure 3.29. The diagram consists of a synchronous while loop with four controls connected to four indicators. This has the simple (and rather useless) effect of showing any modification of a control in the corresponding indicator.

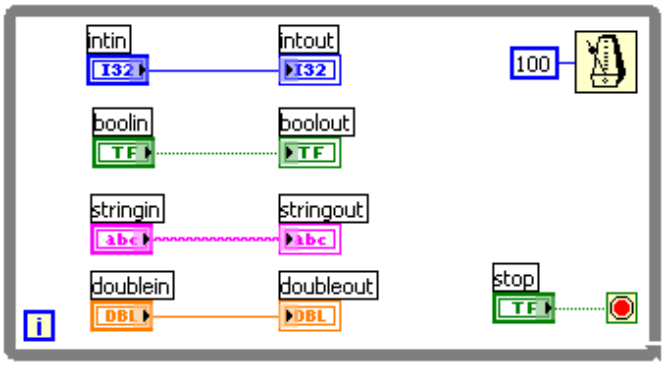


Figure 3.29: Wiring diagram of the example.

Once the VI is published using the JiL Server as described before, the Java code in Listing 3.5 communicates with this VI. The first lines of the `init()` method of this applet instantiate a *Jil* object and try to connect it to the VI running at the `example.uned.es` host at the `8080` port. Once the connection is established, the VI example is opened by invoking the `openVI()` method (see line 11). It then starts the execution of the VI. The following `try/catch` block sets

the values of the four controls and flushes the buffer. The third block reads and prints the value of the VI indicators. The VI must have placed in the indicators the values previously sent for the controls, according to the VI wiring diagram. The final `try/catch` block stops the VI and closes the connection.

Listing 3.5: Java code to communicate with the VI example of Figure 3.29.

```
1  public class SimpleJiLTest extends javax.swing.JApplet {
2
3    String initCmd = "intin(con),boolin(con),stringin(con),doublein(con),
4                     intout(ind),boolout(ind),stringout(ind),doubleout(ind)";
5
6    public void init() { // start connection and run the VI
7
8      jil.Jil vi = new jil.Jil("example.uned.es",8080);
9      try {
10         vi.connect();
11         vi.open(apps/example.vi, initCmd);
12         vi.run();
13     } catch (Exception e) {
14        System.out.println("Error when connecting to the VI");
15     }
16     try { // setting the value of the VI controls
17        vi.setValue("boolin(con)", new Boolean(true));
18        vi.setValue("intin(con)", new Integer(1));
19        vi.setValue("doublein(con)", new Double(0.5));
20        vi.setValue("stringin(con)", "Hello world");
21     } catch (Exception e) {
22        System.out.println("Error when setting VI controls");
23     }
24     try { // reading the value of the VI indicators
25        System.out.println("bool = "+ vi.getBoolean("boolout(ind)"));
26        System.out.println("int = "+ vi.getInt("intout(ind)"));
27        System.out.println("double = "+ vi.getDouble("doubleout(ind)"));
28        System.out.println("String = "+ vi.getString("stringout(ind)"));
29     } catch (Exception e) {
30        System.out.println("Error when readingVI controls");
31     }
32     try { // stop the VI and close the connection
33        vi.stop();
34        vi.close();
35        vi.disconnect();
36     } catch (Exception e) {
37        System.out.println("Error when closing the connection");
38     }
39
40   } // end of the init method
41
42 } // end of class
```

3.3.6 Integrating the API Java in *Ejs*

The previous section provides all the information required by an expert Java programmer to create a complete remote graphical user interface that accesses an existing LabVIEW VI through the Internet. However, to non-experts in Java graphical programming may be difficult to create this interface. To overcome this

limitation, *Easy Java Simulations* was granted the ability to create JiL-enabled applets using the *Jil* library in a transparent way.

As seen in previous sections, *Ejs* allows users to define the model and the view of a simulation in a simple and efficient way. The model must provide an algorithmic description of the industrial process, didactical setup, or physical phenomenon under study. This includes:

a. A list indicating its state, parameters, input, and output variables together with their initial values, and

b. Equations that describe how these variables relate to each other, evolve with time, or change depending user interaction.

The view must provide a graphical representation of the program output and an interface for user interaction. *Ejs* provides a simplified program structure, custom model tools (such as an ODEs editor), and drag-and-drop view elements that allow authors to work at a high-level of abstraction, thus speeding up the creation process. Authors input the qualified information on the simulation that only a human can provide, and the program takes care of all computer-related aspects of creating a finished, independent Java applet or application.

When using *Ejs* to create the remote interface for an existing virtual instrument, there is really no need to specify a model. The behaviour of the process is determined by the real equipment. Variables of the model are meant to help communicate with the VI controls and indicators. The panel indicating variables in *Ejs* was edited to enable authors to enter the URL of a VI published by the JiL Server. *Ejs* then automatically connects with the VI and retrieves the list of controls and indicators and then offers it to the author so that s/he can choose which of them s/he wants to read and write by linking them to the variables declared in the *Ejs* table of variables.

This process was automatized using an interesting feature of the command based architecture. *Metadata information* is shared between client and server as a previous step to the data exchange. By doing this, client and server are informed of the exchange format beforehand, i.e., which variables will be written

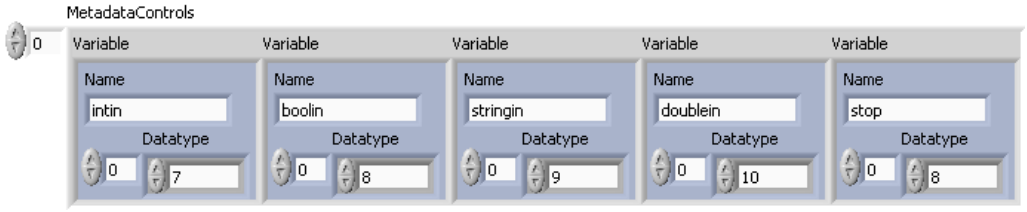


Figure 3.30: Metadata information in LabVIEW for VI controls in Figure 3.29.

and read, and know what their data types and order are. This means, the task of packaging and decoding one variable is simple and known by both ends (server and client) in the first step of the communication. Figure 3.30 shows the *metadata information* generated in LabVIEW as an array of clusters. Each element of the array contains all the necessary information to describe a variable in LabVIEW. For instance, one variable could be described by its *name* and its *data type*.

Listing 3.6: XML variables descriptor.

```
1  <?xml version="1.0" encoding="iso-8859-1"?>
2  <MetadataControls>
3
4    <Variable>
5      <Name>intin</Name>
6      <Datatype>int</Datatype>
7    </Variable>
8
9    <Variable>
10     <Name>boolin</Name>
11     <Datatype>boolean</Datatype>
12   </Variable>
13
14   <Variable>
15     <Name>stringin</Name>
16     <Datatype>string</Datatype>
17   </Variable>
18
19   <Variable>
20     <Name>doublein</Name>
21     <Datatype>double</Datatype>
22   </Variable>
23
24   <Variable>
25     <Name>stop</Name>
26     <Datatype>boolean</Datatype>
27   </Variable>
28
29 </MetadataControls>
```

The JiL server uses an XML document (see Listing 3.6) to describe and to send the *metadata information* extracted from a VI to *Ejs*. The tags of the document define the properties of each element of the array of clusters (variables) allowing the possibility of adding more properties according to the requirements. To access

the variables and their properties in *Ejs*, the JDOM[7] library for Java is used to parse the XML document and to extract the information.

Metadata information is not only useful to edit and connect variables in *Ejs* but also because it enables to JiL server to send just the bytes of the chosen variables by the developer during the definition of the model. In this way, there is no overhead in the data sent from server to client since the JiL server already knows what has to be sent to *Ejs* and how. Otherwise, `getValues` methods would need to send the name of the variable required in every iteration that increases data traffic during communication. Figure 3.31 shows the exchange of messages between *Ejs* and the JiL server when setting up a connection with a VI target.

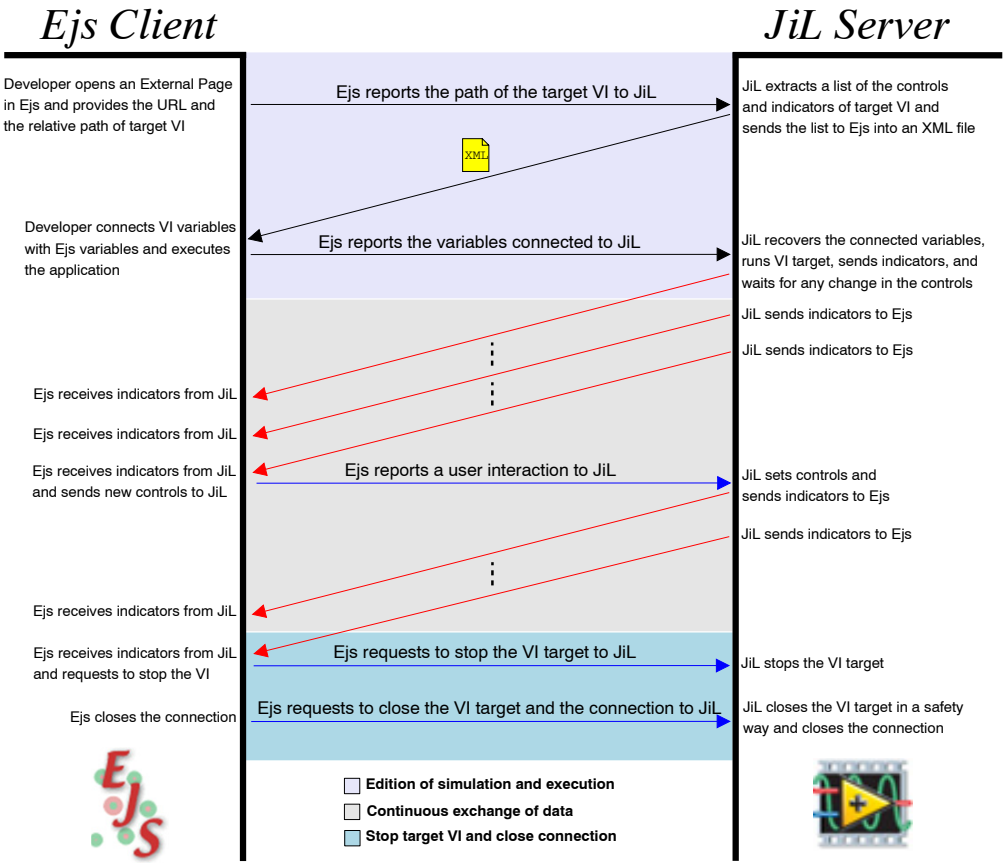

Ejs Client
JiL Server
Developer opens an External Page in Ejs and provides the URL and the relative path of target VI
Ejs reports the path of the target VI to JiL
JiL extracts a list of the controls and indicators of target VI and sends the list to Ejs into an XML file
XML
Developer connects VI variables with Ejs variables and executes the application
Ejs reports the variables connected to JiL
JiL recovers the connected variables, runs VI target, sends indicators, and waits for any change in the controls
JiL sends indicators to Ejs
JiL sends indicators to Ejs
Ejs receives indicators from JiL
Ejs receives indicators from JiL
Ejs receives indicators from JiL and sends new controls to JiL
Ejs reports a user interaction to JiL
JiL sets controls and sends indicators to Ejs
JiL sends indicators to Ejs
Ejs receives indicators from JiL
Ejs receives indicators from JiL and requests to stop the VI
Ejs requests to stop the VI target to JiL
JiL stops the VI target
Ejs closes the connection
Ejs requests to close the VI target and the connection to JiL
JiL closes the VI target in a safety way and closes the connection
Edition of simulation and execution
Continuous exchange of data
Stop target VI and close connection

Figure 3.31: Messages exchange between *Ejs* and JiL server.

All this flow of information between client and server is hidden to the developer and s/he is only limited a few and simple steps. Figures 3.32 and 3.33 illustrate how it applies to *Ejs* for sample VI in Figure 3.29.

[7]JDOM is an open source Java-based document object model for XML that was designed specifically for the Java platform so that it can take advantage of its language features.

Note the "External File" field in Figure 3.32 with the URL of the sample VI file. The syntax is: `<labview:IP_address:port>VI_relative_path`.

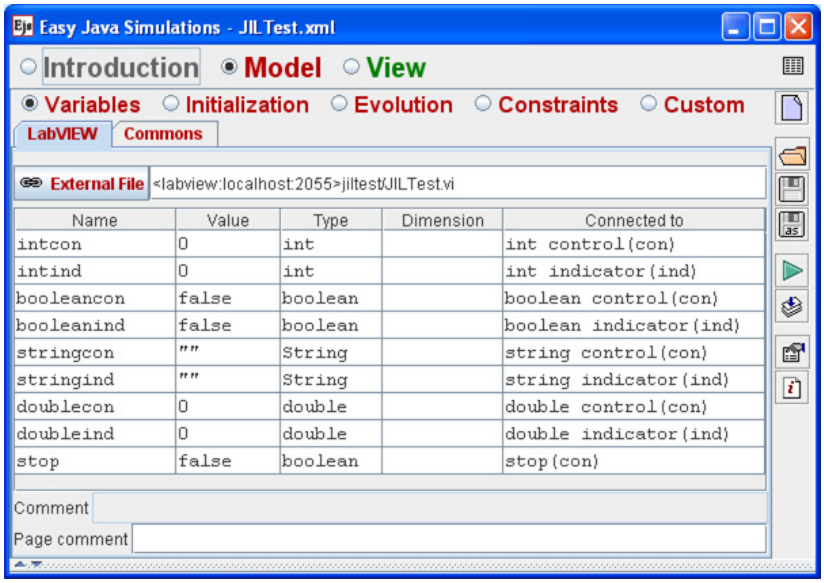


Figure 3.32: Table of *Ejs* variables linked to VI controls and indicators.

The `labview` keyword identifies the file as a JiL-enabled remote VI. The `IP_address` and `port` values indicate the URL at which the JiL server is listening. Finally, the `VI_relative_path` value indicates the location of the VI in the JiL server. Once provided the "External File" field, *Ejs* requests the set of controls and indicators of target VI to JiL server.

In the case of each variable declared in the table, by clicking on the "Connected to" cell, the dialog window in Figure 3.33 pops up, allowing the author to browse

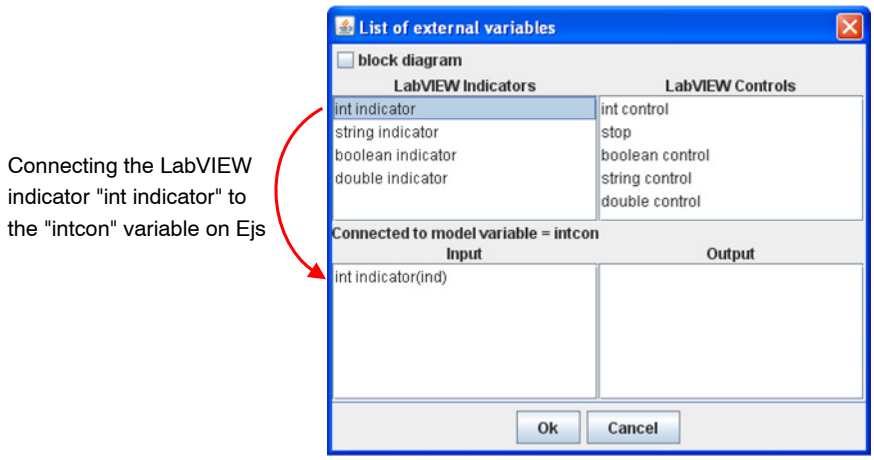


Figure 3.33: List of controls and indicators of a remote VI as offered by *Ejs*.

the list of VI controls and indicators and select the one desired. Checking the "block diagram" check box in this dialog enables *Ejs* to display the VI wiring diagram for additional information.

Establishing this simple connection between model variables and VI controls and indicators instructs *Ejs* to include the necessary Java calls to the library *jil.Jil.class* (integrated in *Ejs*) in the generated simulation, in order to pass the values of the variables back and forth as required by the program. Connection to (and disconnection from) the VI is however left explicitly to be coded by the author so as to adapt to this program's logic. In this context, the methods from *jil.Jil.class* have been encapsulated in a new reduced set of built-in methods of *Ejs* that the author can use to program the logical sequence of connection with the Jil-published VI. Table 3.4 describes these methods and their functionality.

Table 3.4: Methods in *Ejs* to link with a Jil published VI.

Ejs built-in methods to control the connection with JiL server
`_external.connect()`: Initializes the TCP/IP connection with the JiL server.
`_external.disconnect()`: Closes the TCP link with the JiL server.
`_external.runVI()`: Starts the VI.
`_external.stopVI()`: Stops the VI.
`_external.step()`: Performs the data exchange between *Ejs* and JiL Server.
`_external.synchronize()`: Updates controls when user interacts with the view.
`_external.isConnected()`: Returns the current status of the TCP/IP connection.

This reduced set of methods makes facilitates the connection and the exchange of data with JiL server. For example, the `_external.connect()` method calls the `openVI(String modelPath, String initCmd)` method from *jil.Jil.class* internally using the information provided by the developer when s/he introduces the URL of the remote target VI and associates variables as shown in Figures 3.32 and 3.33. Similarly, the `_external.disconnect()` method calls the `closeVI()` method from *jil.Jil.class* internally to close the VI and disconnect from the server side. On the other hand, once the connection has been established and the VI has been executed calling the `_external.runVI()` method, the `_external.step()` method must be used in the "*Ejs* evolution" to start the data exchange. This last method contains the sequence of *get* methods necessary to know about the state of the remote VI, i.e., the value of indicators. The `_external.synchronize()`

is used to update the current value of every control in the remote VI that have been connected to the *external variables page* (on an internal level it calls the *set* methods). This means, the exchange data between *Ejs* and LabVIEW is performed in an asynchronous way given that *Ejs* is receiving the state of the process continously while a sending is produced just when user interacts with any element of the *view*.

Authors can now use the *Ejs* model variables in the construction of their view, either for visualization or interaction purposes, just as in any other *Ejs* generated view, obtaining direct access to the VI controls and indicators. Authors need to take into account, however, that variables connected to VI controls should be considered as write-only, and variables connected to VI indicators as read-only variables.

3.4 Conclusions

The methodology proposed in this chapter provides a structured framework for new developments of on-line experimentation systems. The move from former applications mentioned (whereby all components in the server and client were mixed within a single program) towards a module-based architecture has allowed to reduce the amount of effort to create new virtual and remote laboratories. The *command-based architecture* is a particularly appropriate solution to organize low-level programming details to communicate embedded applications to a remote host via networking protocols such as TCP or UDP. Furthermore, this architecture presents a well-defined and expandable structure allowing the addition of new commands to enhance the system's intelligence.

On the other hand, *Ejs* and LabVIEW, evidently have all the features needed to enable the development of on-line experiments following a client-server approach. The following chapter presents some examples of web-based remote and virtual control laboratories created applying the approaches described here.

4

Prototypes Developed

Overview

The various prototypes presented in this chapter summarize the concepts, implementation details, and aproximations exposed in Chapter 3.

Following the guidelines indicated for the *experimentation layer*, three virtual and remote control laboratories were created. Each one was specially chosen to satisfy certain security and stability requirements when real equipments are remotely handled.

The *model-view-control* paradigm is first used to design the *virtual version* (model-based) of every laboratory. In this particular case, *Ejs* allows the creation of powerful simulations in Java language applying this framework. Once the virtual version of the laboratory has been obtained, the sequence of steps needed to include *remote experimentation* into the virtual-lab is as follows.

The main goal of this chapter is to show how to apply this methodology mentioned in previous chapter and serve as a reference guide in the development of new on-line experimentation laboratories.

4.1 Case studies: A short introduction

The following sections describe how three examples of virtual and remote laboratories in the scope of automatic control have been developed: the *three-tank system*, the *heatflow system*, and the *DC motor*. These three environments are part of the current infrastructure of laboratories that the Department of Computer Science and Automatic Control of the Spanish University for Distance Education (UNED) provides to students for remote experimentation through the Internet.

This set of virtual and remote control labs have been developed using the approach introduced in Section 3.3.6. The steps followed to build the prototypes can be summarized as follows:

a. Designing and implementing, a Java applet based on an mathematical model of the real process and an appropiated user interface using *Ejs*.

b. Creating a LabVIEW VI to control the real process in *local mode*.

c. Publishing the LabVIEW VI using the JiL server.

d. Modifying the applet to connect with the local VI published by the JiL server. The applet's user interface is also adapted so that it can visualize either the data generated by the computer model or the data received from the VI that controls the real equipment.

These web-based applications have been developed to explain PID control concepts in an introductory course on automatic control. Nevertheless, these could be modified at a later stage in order to introduce advanced control strategies and adapt the labs to higher level courses. The framework based on the JiL server and *Ejs* presents certain advantages when the communication layer is separated from the control loop on the server-side.

First of all, a complete overview of the implementation of the three-tank system control laboratory is provided in order to illustrate the details of the development methodology. This approach is then replicated to describe the other two case studies.

4.2 Prototype I: The Three-tank system

Figure 4.1 corresponds to the DTS200 three-tank system manufactured by Amira GmbH (Amira 2009).

Figure 4.1: The DTS200 three-tank system by Amira.

The three-tank system is suggested as a benchmark system used for different purposes. It can be used as a test system for fault detection and identification, as well as for reconfigurable control (Heiming & Lunze 1999). It was positively welcomed for its interesting properties in both control education and research. The system exhibits the typical characteristics of a constrained hybrid system (Mignone 2002) and has proven useful to serve as a test-bed for algorithms related to state estimation, and control or identification of hybrid systems. For these reasons, the three-tank system is used to show the results of different control strategies and as an educational tool in teaching advanced control techniques.

4.2.1 System overview

The three-tank plant consists of three cylinders T_1, T_2, and T_3 with the same cross-section A. These cylinders are connected serially to each other by cross-section S_n pipes. Figure 4.2 shows the plant's full structure.

The right-hand side of tank T_2 has a single outflow valve (through which Q_{20} flows) that has also a circular cross-section S_n. The liquid flowing out of the system is collected in a reservoir located under the three tanks. This reser-

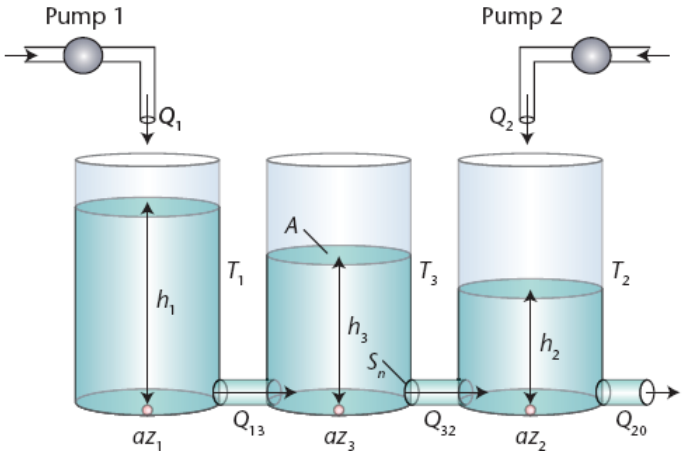


Figure 4.2: The three-tank system. From left to right, tanks T_1, T_2, and T_3 are serially connected to each other by pipes.

voir supplies pumps 1 and 2 with liquid, which eventually returns to the system (pumps 1 and 2 represent the input flows of tanks T_1 and T_2). In this closed system, the liquid that enters the reservoir from the tanks returns to the tanks via the pumps. However, these pumps automatically switch off when the liquid level of T_1 or T_2 exceeds a given upper limit.

In addition to the outflow valve at T_2, the system has five more valves. Two of them connect two consecutive tanks (one for the T_1 to T_3 connection, through which Q_{13} flows, and the other for the T_3 to T_2 connection, corresponding to the Q_{32} flow) and can be manually adjusted to close the link between them. The other three are leak valves located at the bottom of each tank that can be used to drain the tanks manually.

Pump flow rates correspond to process input signals; the levels of liquid in tanks T_1 and T_2 represent the output signals. System users can manage all these signals for control purposes.

The mathematical modelling of the process and the control strategies applied to the system are analyzed in Appendix A (Section A.1). The analysis was carried out to introduce students to *multivariable systems control (2x2)*, *decentralized controller*, *tunning controllers*, *variables interaction* and *stability*. However, this development is not described in the following sections since we are focusing on the technical aspects of the building of the web-based laboratories using the approach mentioned in the previous chapter.

4.2.2 The three-tank system's virtual-lab in *Ejs*

The step by step creation of the virtual laboratory for the three-tank system is described hereafter. The starting point implies to define the process model used in terms of their variables, which hold the different possible states of the process, and relationships among these variables.

Defining the "Model"

A detailed explanation of the main *Ejs's* windows whereby the model is defined is presented below. This description focuses on the *Ejs* sections that will be modified later to add tele-operation capabilities to the virtual-lab.

Variables. Eight pages define the model's variables (*Common*, *Tanks*, *Pipes*, *Leaks*, *Pumps*, *Status*, *PID Control*, *setLanguage*). Each has a name that identifies it according to its purpose (see Figure 4.3).

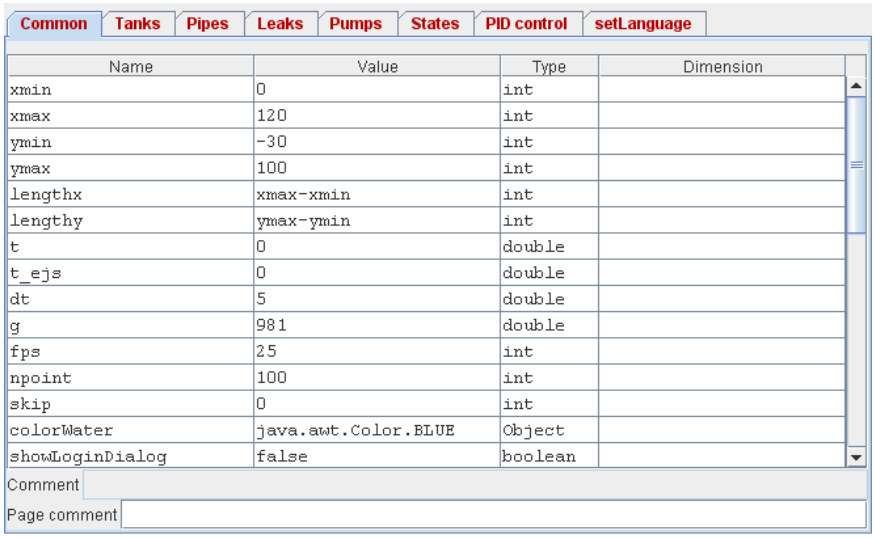
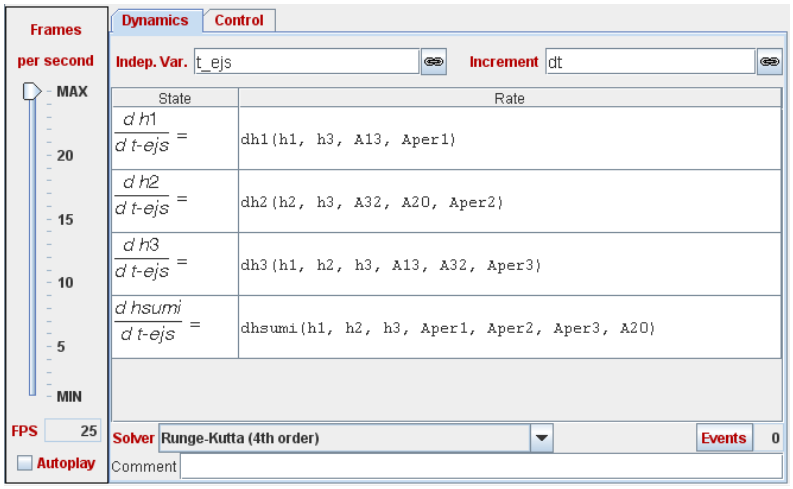
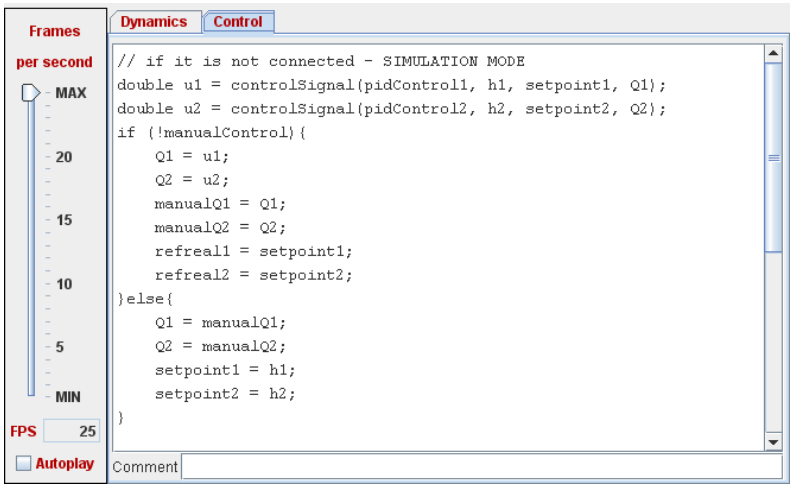


Figure 4.3: *Ejs Model* of the three-tank virtual-lab: **Variables**.

Evolution. In this section, two pages were created (*Dynamics* and *Control*). The first one shows the differential equations' editor of *Ejs* with the definition of the mathematical relationships representing the three-tank process (see Figure 4.4(a)). The second page displays a small fragment in Java showing the logic that governs the system during its evolution (see Fig-



(a) ODEs.



(b) Control logic.

Figure 4.4: *Ejs Model* of the three-tank virtual-lab: **Evolution**.

ure 4.4(b)). In this case, the page shows the switching between manual or automatic control.

Custom. This section is composed of five pages that define a set of customized Java methods (*ODEs*, *Interface*, *ControlSignal*, *saveFragments*, and *setLanguage*). The first page contains the definition of methods that describe the dynamics of the process by ordinary differential equations (see Figure 4.5). These functions are called from the page *Dynamics* of the section *Evolution*. The second and third page define the discrete PID controller and associated methods used to modify control parameters (K_p, T_i, and T_d) on-the-fly. The fourth page contains methods used to save the values

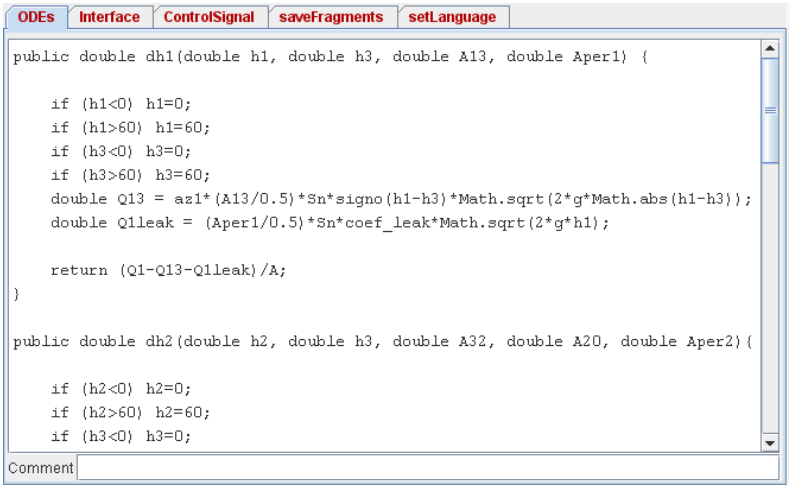


Figure 4.5: *Ejs Model* of the three-tank virtual-lab: **Custom methods**.

of the main system variables in a text file during a practical session. Finally, the internationalization of the application is also completed through the use of the Java I18N feature (Java 2009). Thus, the fifth and last page describing the model contain methods used to switch between English and Spanish languages.

Defining the "View"

The GUI of the three-tank system virtual-lab is created based on the set of graphical elements provided by *Ejs* (see Figure 4.6). In order to keep a uniform structure in each lab prototype, the interface is divided into four zones whereby each area contains a set of graphical elements designed for a specific function.

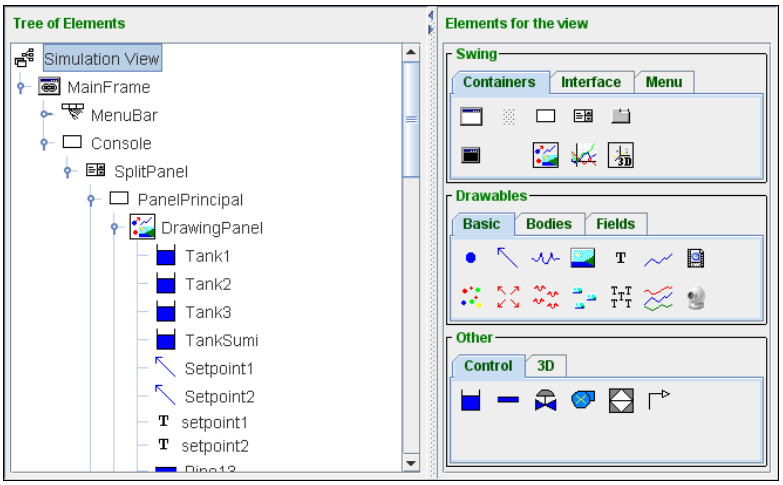


Figure 4.6: *Ejs View* of the three-tank system virtual-lab.

Figure 4.7 shows the applet's main window. The *Graphical view* displays the plant's schematic representation in virtual mode. The plant's schematic representation is meant to be as self-explanatory as possible. Students can easily visualize the system's components and see how the liquid levels in the tanks change according to different valve and pump parameters. The plant's behaviour is simulated using the software model defined in Figure 4.4(a) and Figure 4.5 based on the equations listed in Appendix A (see Section A.1.1).

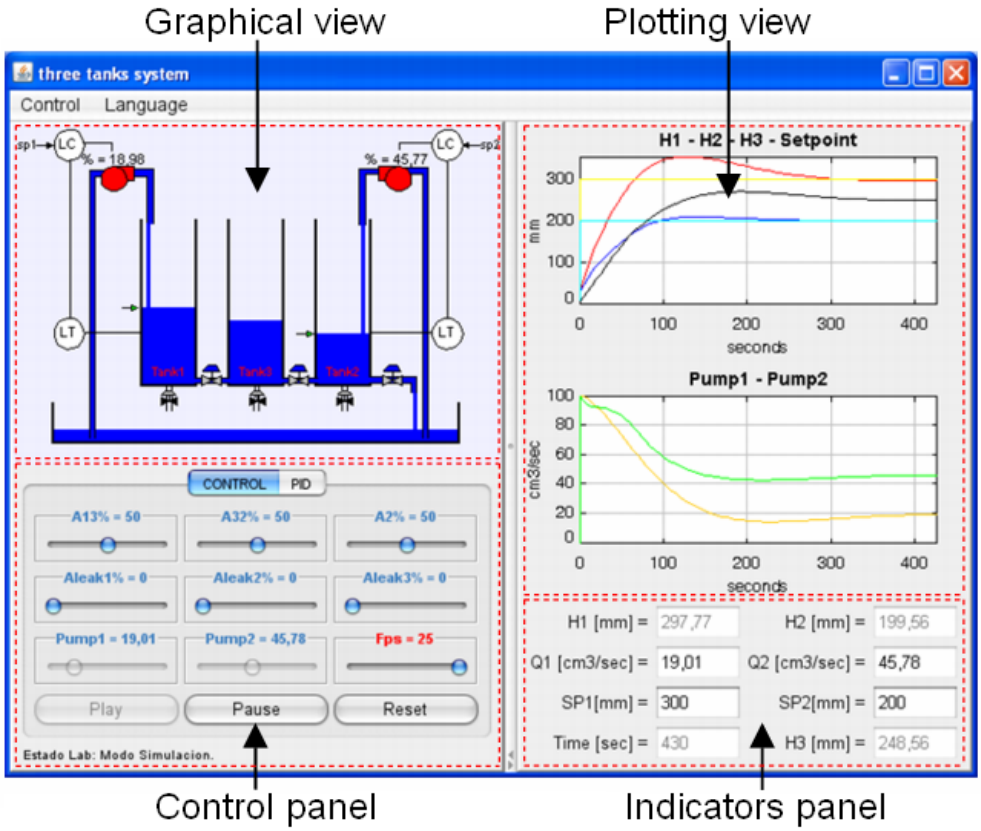


Figure 4.7: GUI of the three-tank system virtual-lab.

Students can play, pause, and reset the simulation using three push buttons from the *Control panel*. They can also modify the percentage of opening of the connecting (A13%, A32%, A2%) and draining valves (Aleak1%, Aleak2%, Aleak3%). If the system is in *manual mode*, the student can control the flow supplied by the pumps with two sliders located in the lower part of the applet's main window (Pump1 and Pump2). Moreover, two small arrows placed on the sides of tanks T_1 and T_2 allow to change the setpoints when the system is in *automatic mode*. Students can modify these setpoint values interactively by dragging the

arrows up and down. Furthermore, they can also tune the control parameters for optimal performance by checking the "PID" tab whereby a second window lets users adjust the values of the controller parameters.

The *Plotting view* area displays signal scopes of the controlled and manipulated variables. It is located at the top right-hand part of the interface. The upper scope plots the levels of the two tanks T_1 and T_2 (the controlled variables) and their setpoints. The lower scope displays changes occuring in control variables, that is, the voltages applied to the pumps.

Finally, the *Indicators panel* located on the right lower part contains a set of numerical indicators displaying the instantaneous value of the main variables of the system such as the simulation time, the tanks level in millimeters, and the setting of the pumps and setpoints.

Through a menu bar located at the top of the main window, users can switch between manual/automatic control mode by clicking in the *Control* menu and also by changing the language of the interface with the *Language* menu.

Steps to take in order to include remote experimentation options to the virtual-lab are described hereafter. Section 4.2.4 specifically describes modifications made to this template (the virtual-lab) in order to add these features to the application.

4.2.3 Local control of the three-tank system in LabVIEW

The first step in the development of the server-side components is to generate a VI to control the real system locally. Figures 4.8 and 4.9 show the block diagram and the front panel of the LabVIEW application created according to the structure described in Section 3.3. In particular, the block diagram in Figure 4.8 shows the *flat sequence structure* of LabVIEW that divides the execution flow of the application into three stages:

1. Initialization of the hardware.
2. Acquisition and closed-loop control (HIL - Hardware in the Loop).
3. Reset of the hardware.

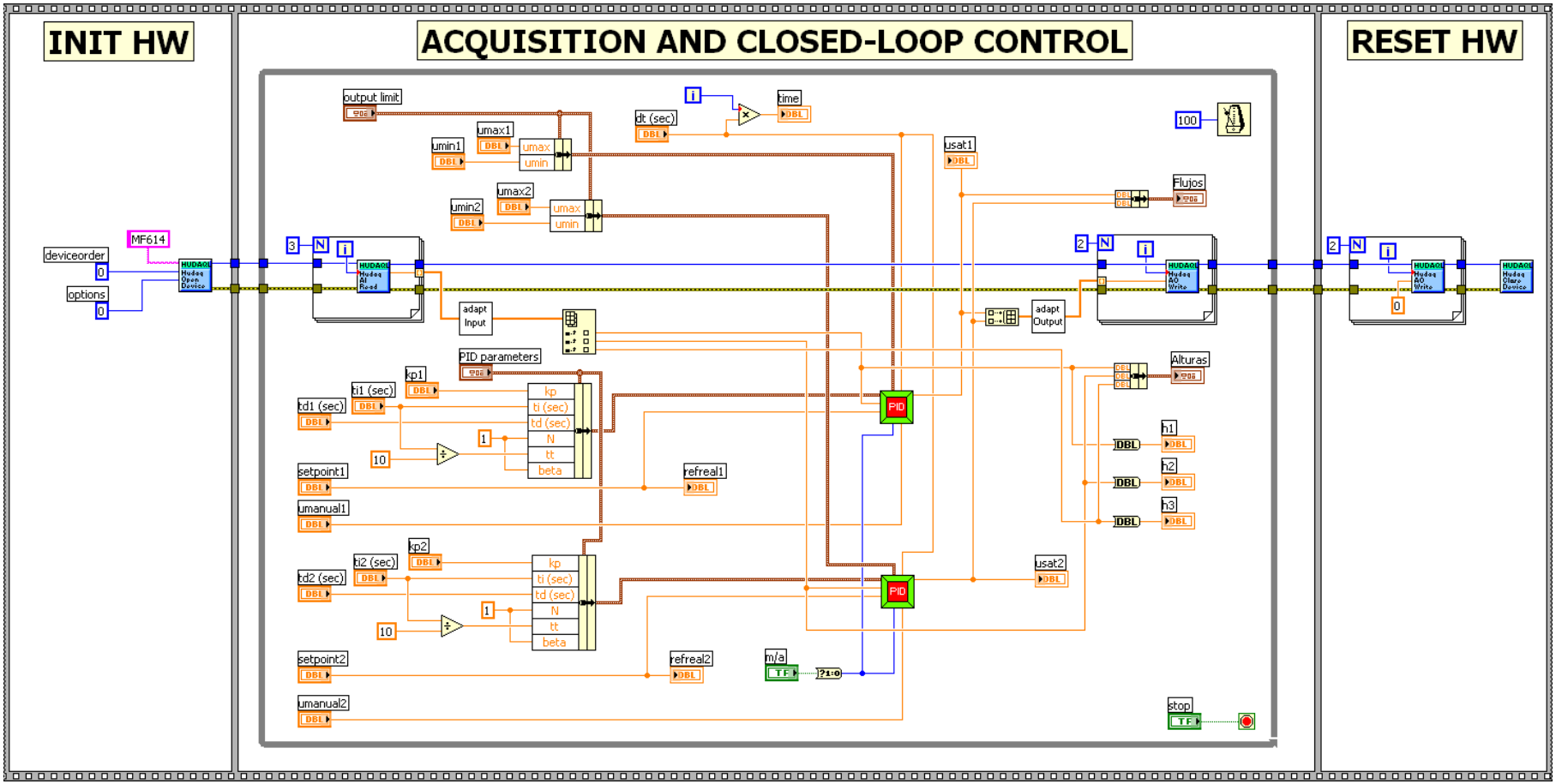


Figure 4.8: Local control of the three-tank real system - Block diagram.

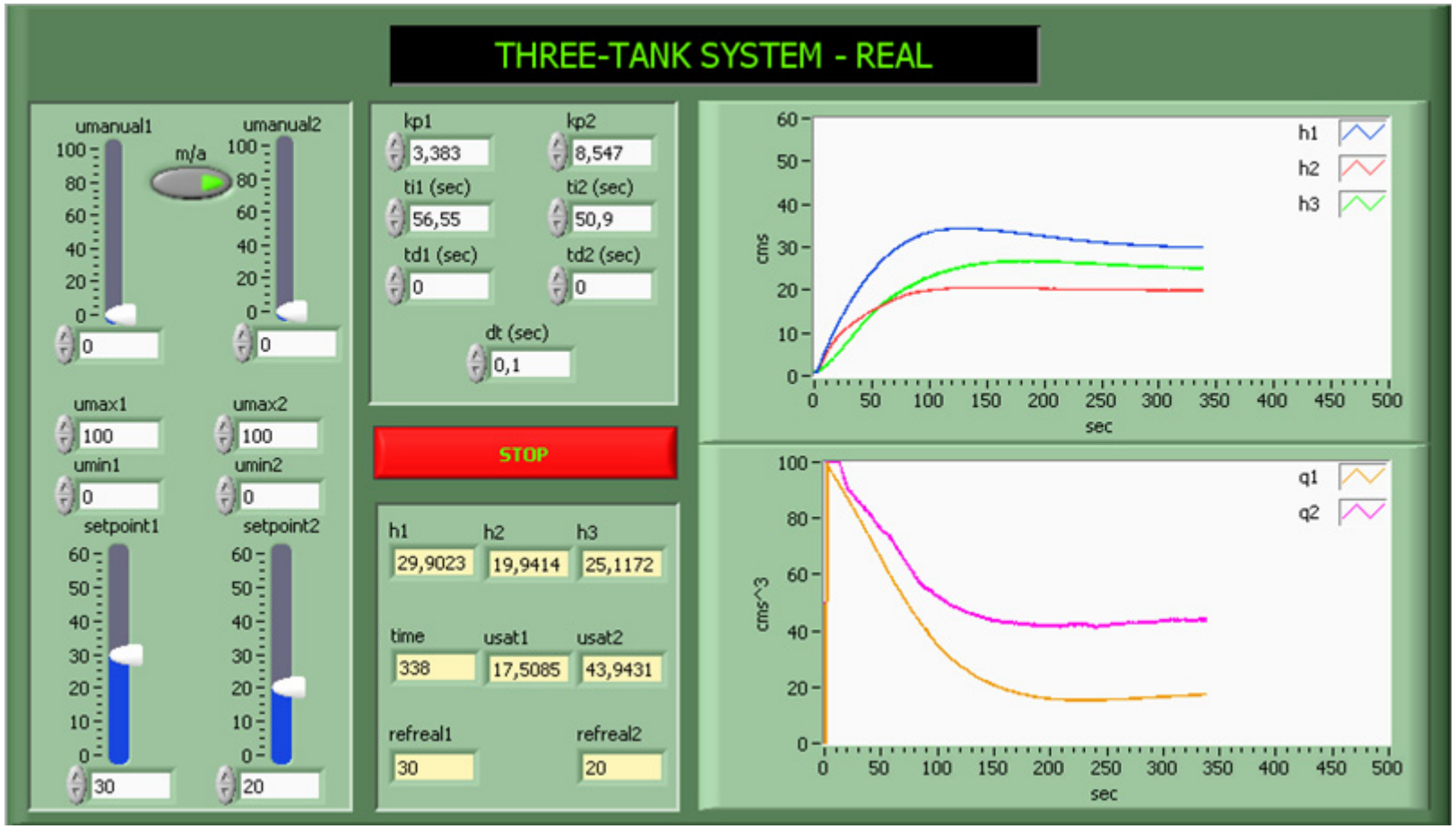


Figure 4.9: Local control of the three-tank real system - Front panel.

The first and third stages are self-explanatory. However, the intermediate stage contains some technical issues described below. The LabVIEW application implements a *descentralized multivariable control strategy* (see Section A.1.2 in Appendix A). This kind of control strategy can be applied to systems for which the interaction between variables is minimal and therefore, every measured variable can be controlled by means of one manipulated variable in independent control loops. In this case, the liquid level in tank 1 (H_1) and tank 2 (H_2) is regulated by manipulating pump 1 (Q_1) and pump 2 (Q_2), respectively. The control algorithm in each loop is a standard PID controller (see Figure 4.10) with set-point weighting, anti-windup mechanism, and filtering of the derivative action (Åström & Hägglund 2006).

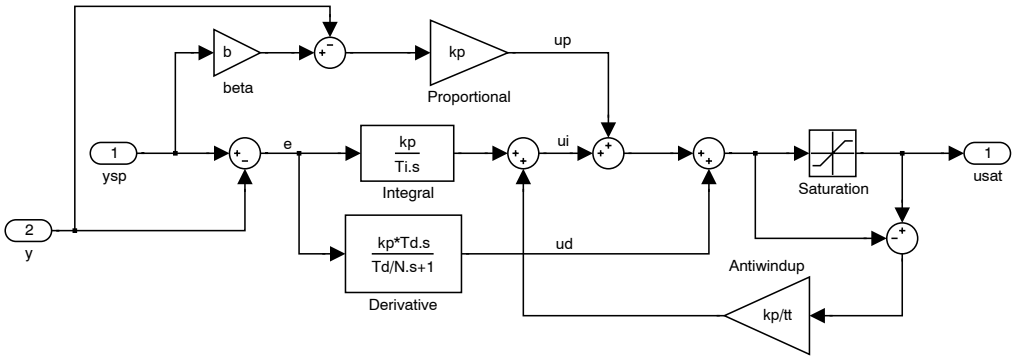


Figure 4.10: Continuous PID controller (Simulink model).

Figure 4.11 shows the discrete version of the PID controller programmed in LabVIEW. Figure 4.11(a) depicts the subVI developed for the local control of the three-tank system and Figure 4.11(b) shows the internal implementation of the algorithm programmed using a *Formula Node*[1] structure of LabVIEW.

A key issue to take into account when creating the local control application is how to stop the VI in a safe way. This is a critical point since this expensive piece of equipment will be remotely manipulated by students and, therefore, safety actions should be designed to avoid damages in the hardware. For this reason, actions taken should fulfill certain requirements as mentioned in (Salzmann & Gillet 2008). Some of these requirements are:

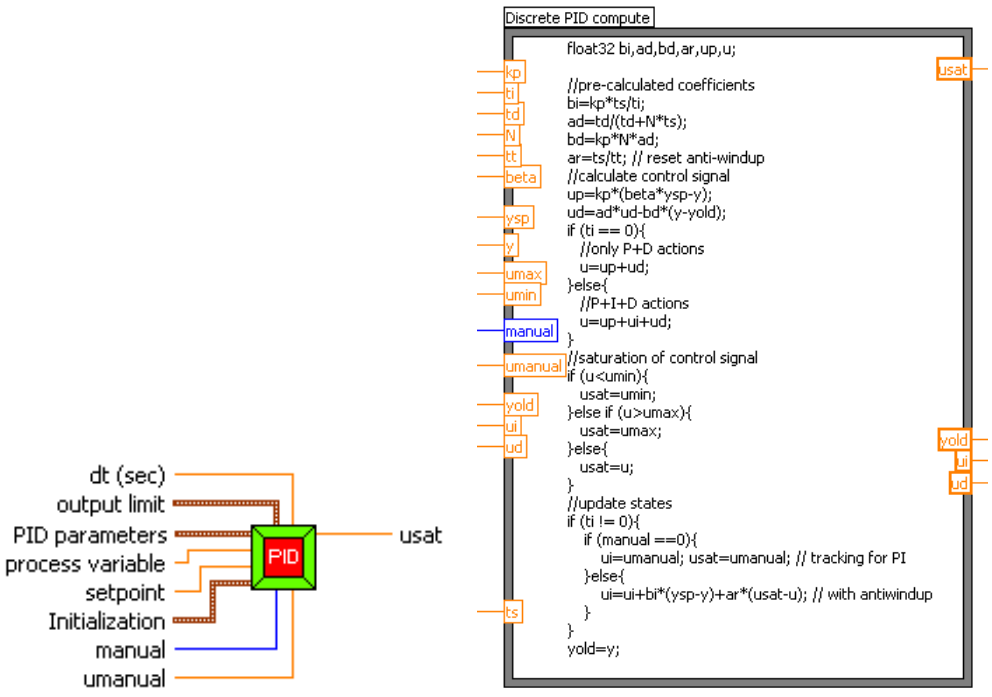
[1]The Formula Node is a text-based node available in LabVIEW to perform mathematical operations in a block diagram with a C-like language. Formula Nodes prove useful to write complex equations and use existing text-based code.

1. The physical equipment should be *identifiable* so as to define what kind of equipment is connected.

2. The equipment should be fully *controllable* and *diagnosticable* by the local computer.

3. For safety reasons, the full controllability of the physical equipment may not be exposed to the outside world. *Controllability also implies that it is always possible to place the equipment in a known state.*

4. Other requirements such as *reliability* and *maintainability* should also be considered.



(a) VI for PID control algorithm. (b) LabVIEW Formula node.

Figure 4.11: Discrete PID controller with antiwindup protection programmed in LabVIEW.

In this particular context, all the prototypes described in this chapter follow a common structure so as to comply with these requirements. The three-tank system disposes of a boolean variable called *stop* to finish the application so that when this variable is pushed in the LabVIEW application the execution gets out from the main while loop and the *reseting code* is then executed before the end

of the application (see RESET HW sequence in Figure 4.9). The *reseting code* could just consist in zeroing the pumps and, finally, reseting the hardware or any additional code in order to move the real process to a known and safe state. The three-tank system also has a hardware safety system that automatically zeroes the pumps when the liquid exceeds a certain level.

Once the VI is ready to run in local mode, the application is published by the JiL server. Developer is only required to place the main VI of the local control application into the *apps* folder of the JiL server. Thus, the publication procedure ends here and no additional work is needed.

Summarizing, the JiL server helps developers to fulfill the safety requirements above mentioned since:

- ✔ If the connection with the client is lost, the JiL server automatically looks for a boolean variable named *stop* in the local control VI to finish the application in a safe way (*controllability*).
- ✔ Extra *reliability* and *maintainability* were gained by creating a generic communication module independent from the control task.

4.2.4 The virtual and remote version of the laboratory

In order to let the three-tank system's virtual-lab to connect and manage the local control VI published by the JiL server, certain programming modifications must be made in *Ejs*. Much of this work has already been explained in the previous chapter (Section 3.3.6) and therefore, the description of this case study reinforces the correct application of this approach.

Steps taken to link the virtual *Ejs* application of the three-tank system to the VI published by the JiL server are described hereafter:

Step 1. A new **External Variables Page** to link the *Ejs* and the LabVIEW variables is created. Figure 4.12 shows how this was done for the three-tank system. On the upper part, the URL `<labview:62.204.199.106:2055>threetank/threetankReal.vi` points to the VI *threetankReal.vi* published by the JiL server. If the URL is correct then *Ejs* receives the list

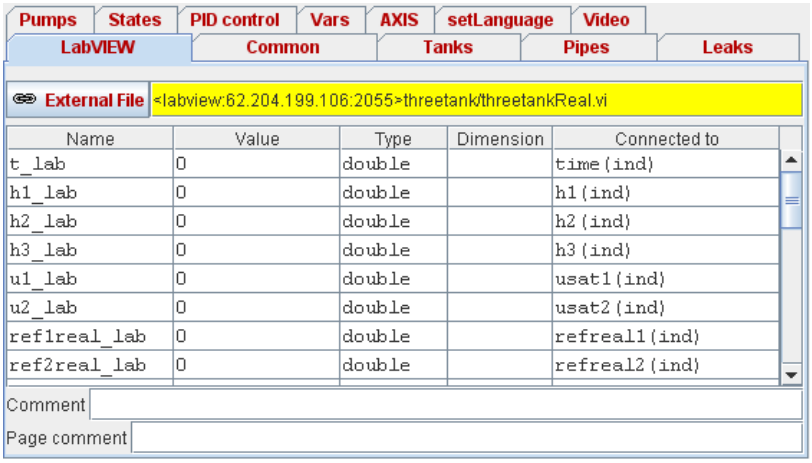


Figure 4.12: Linkage of the *Ejs* and LabVIEW variables.

of controls and indicators of the target VI. Finally, the variables linkage is completed in a similar way as described in Section 3.3.6.

Step 2. Built-in methods in *Ejs* are used to program the logic of the connection with the VI that controls the three-tank system published by the JiL server. These methods belong to an *Ejs* internal Java class so-called *_external*. An instance of this class is automatically generated once the *External Variable Page* has been created. The Java code presented in Figure 4.13 shows how these methods were used to link the three-tank system's virtual-lab to the JiL server. At low-level, the methods to *open* and/or *close* a connection with the JiL server are used and, simultaneously, the methods to control the *starting* or *stopping* of the target VI.

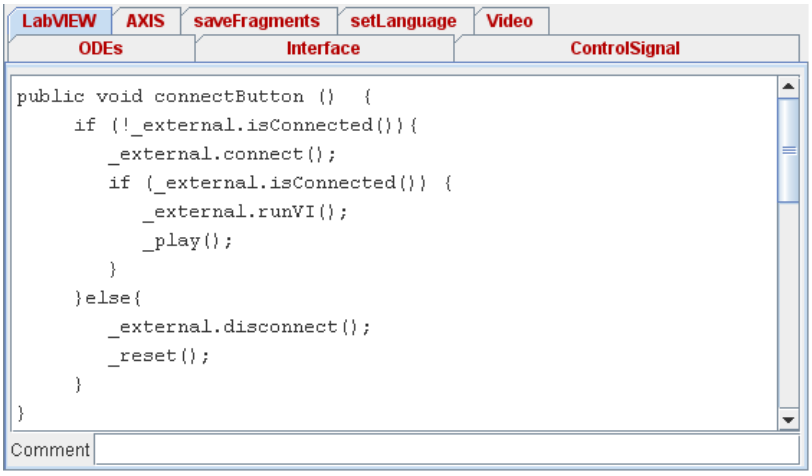


Figure 4.13: Method to be launched when *connect* button is pushed.

In Figure 4.13, the custom method `connectButton()` initializes the connection with the server. When connection is established, the remote VI is then started by calling the `_external.runVI()` method.

Figure 4.14 depicts the modifications to make in the *Evolution* pages of the virtual-lab. In this case, an `if-else` instruction has been added to differentiate between simulation or remote mode. When working in remote mode the `_external.step()` method is invoked to obtain the values of all indicators from the JiL server. Otherwise, the state of the process is updated by solving the ODEs modelling the process.

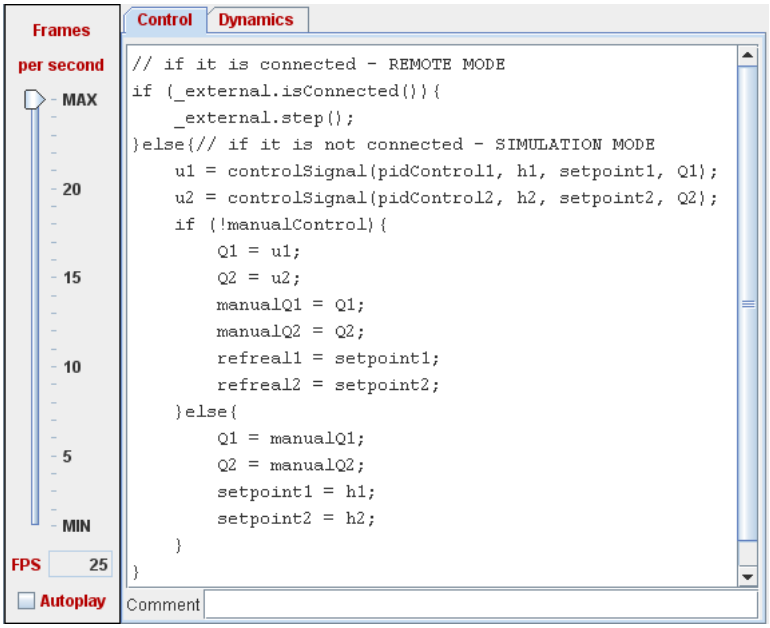


Figure 4.14: The `_external.step()` method is called in every iteration of the *Evolution* during the connection.

As described, the `_external.synchronize()` method is used to report any user interaction with the GUI to the JiL server.

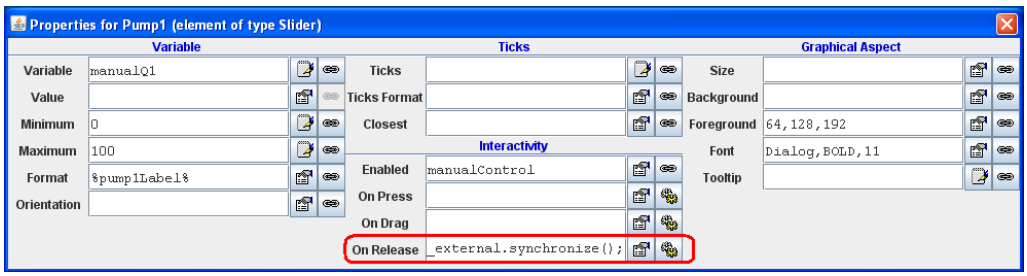


Figure 4.15: The `_external.synchronize()` method is called when user modifies the value in pump1 manually.

Figure 4.15 shows the properties window of the slider in the control panel associated with pump 1. The `_external.synchronize()` method is called in the **On Release** property of the slider so that when the mouse is released from this element, the method is triggered.

Step 3. Finally, visual feedback is included by using the **WebCamImage** element of *Ejs*. Figure 4.16 shows the tree of elements used to compose the *view* of the application. The **WebCamImage** is placed in first position in the hierarchy for a *view* with augmented reality.

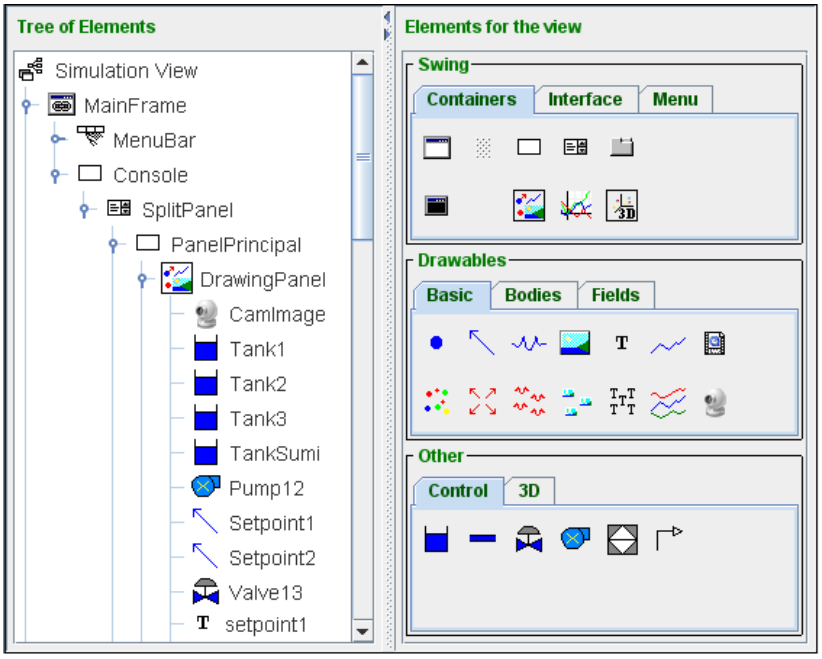
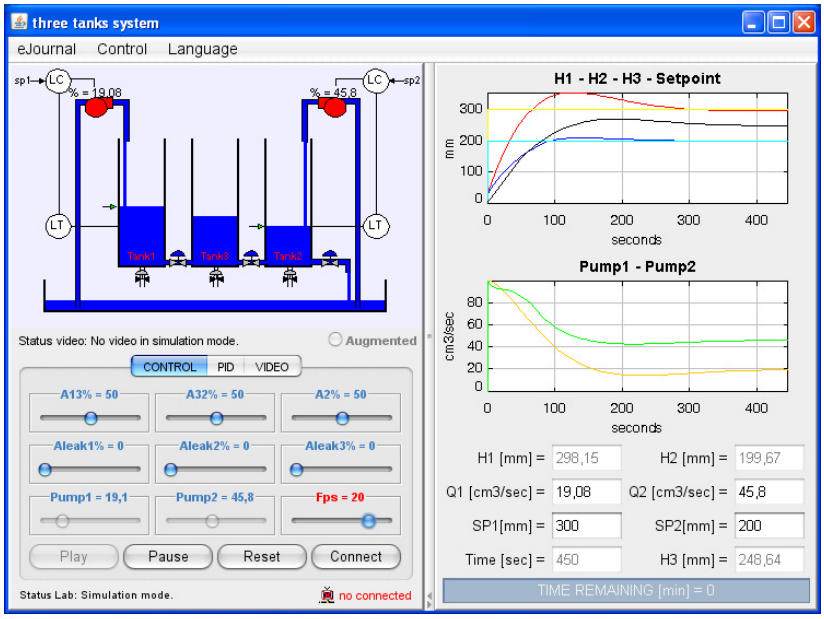


Figure 4.16: The **WebCamImage** appears at the top of the hierarchy of the DrawingPanel container to enrich the view with augmented reality.

The final graphical user interface of the three-tank system's web-based laboratory can be seen in Figures 4.17 and 4.18. Figure 4.17(a) shows the GUI working in simulation mode. We can see that it is similar to the virtual-lab developed in Section 4.2.2, however, a few changes were made. A new button named *Connect* was placed at the bottom-right corner of the control panel. By pushing this button, the user connects with the server side since the `connectButton()` method (see Figure 4.13) is invoked. Figure 4.17(b) shows the GUI working in remote mode when clicking on the *Connect* button. The graphical representation of the process is replaced by video images captured from the IP camera located in the

remote laboratory of the university while the main variables of the interface are updated with data obtained from the JiL server.

One should highlight the fact that the tabbed panel of the interface has a new element named "VIDEO". This tab contains a cluster of six buttons which allow to observe the process from different perspectives through video images. In particular, Figure 4.18(a) shows the upper part of tank 1 that corresponds to the perspective obtained when pressing button *Top Tank1*.



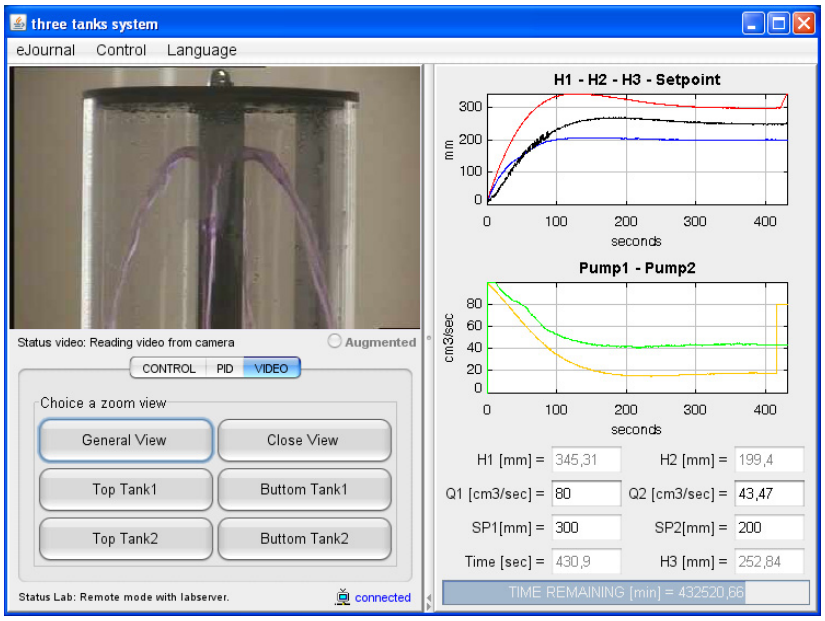
(a) Final GUI in simulation mode.

(b) Remote mode with video feedback.

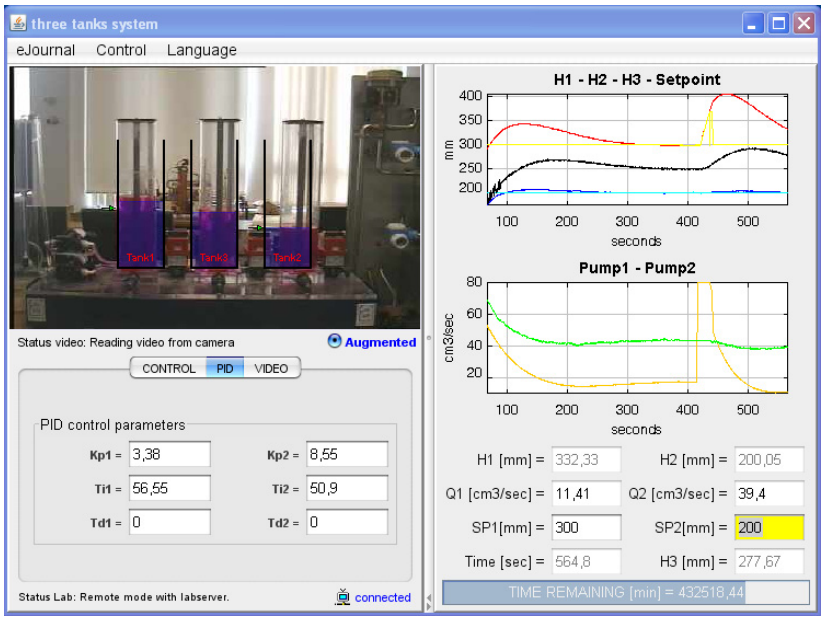
Figure 4.17: The three-tank system virtual and remote control laboratory.

Finally, Figure 4.18(b) depicts how the augmented reality concept was included. Here, the virtual representation of each tank is kept visible overlapping the video images of the remote process. The arrows located on the side of the tanks 1 and 2 are also visible. Users can change the setpoint value for tanks 1 and 2 interactively by dragging and dropping these elements.

The upper menu of the graphical user interface includes an additional element named *eJournal*.



(a) Example of the video options.



(b) Remote mode using augmented reality.

Figure 4.18: The virtual and remote control lab of the three-tank system.

These options available in the menu allow users to save, for example, a snapshot of the *Plotting view* area as an *image file* (*.gif) or the evolution of the main state variables as a *binary or text file* (*.dat or *.txt) in the local hard disk.

We have finished describing the first prototype of a web-based control laboratory. A brief summary of the steps to follow in order to develop it and deploy it later in the Internet is provided hereafter. Figure 4.19 is used as a reference to specify the most important issues to take into consideration.

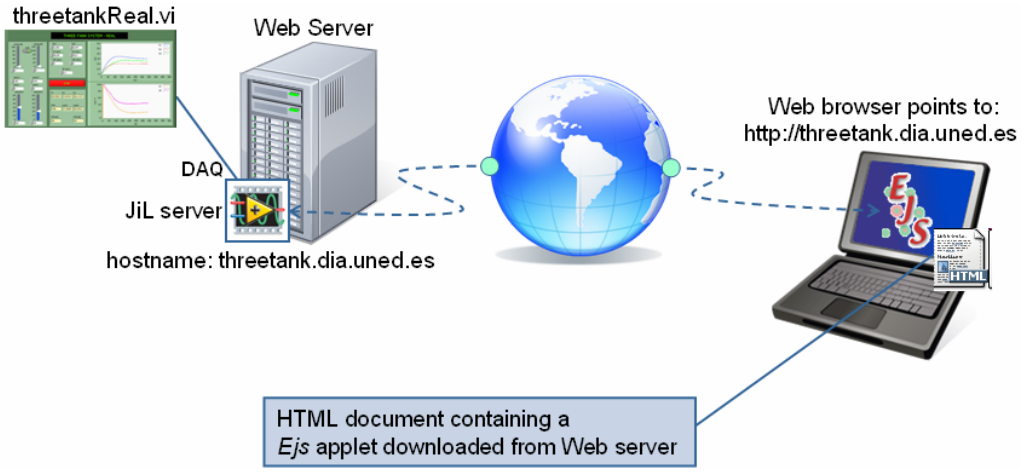


Figure 4.19: Connection scheme via web browser between *Ejs* and LabVIEW. The *Ejs* application controls the threetankReal.vi through the JiL server.

These steps can be enumerated as follows:

1. **LabVIEW server-side apps (JiL server + local control VI)**. The JiL server and the local VI are running in the server and waiting for client connections. The server can be reached from any host in the Internet.

2. ***Ejs* client-side application**. A Java applet must be generated from the standalone application created with *Ejs* and published by a web server. This applet controls the *threetankReal.vi* through the JiL server.

3. **Web server to publish the Java applet created by *Ejs***. A web server should be installed in order to host the web site that provides the Java applet embedded in an HTML page.

4. **Web browser to download the Java applet from server**. A web browser is used to enable clients to have access to the web-based laboratory.

In the example of the three tank system, the web site can be accessed from `http://threetank.dia.uned.es`, whereby `threetank.dia.uned.es` is the domain name assigned by the DNS server that manages the root domain.

So far, we have seen in detail how to put the methodology introduced in the previous chapter to create a web-based control lab of the three-tank system into practice. Since these application are very specific, their implementation will differ in each case. The four points mentioned in Section 4.1 should provide a set of guidelines for potential developers to follow. ➠ Outcomes of this work was published in (Duro et al. 2008, Dormido-Canto et al. 2008).

In the following section, we will see how the same mechanism is used to create the other two lab prototypes. However, to avoid repeating the steps previously mentioned in this case study, the explanation will exclusively describe the local control VI and the final GUI of each laboratory.

4.3 Prototype II: The Heatflow system

The Heatflow system was developed by Quanser Consulting (see Figure 4.20). It allows to study concepts of temperature flow control, transport lags and identification techniques (Quanser 2009).

From a practical point of view, the graphical representation of the process in *Ejs* offers some interesting challenges since the temperature flow is not perceptible

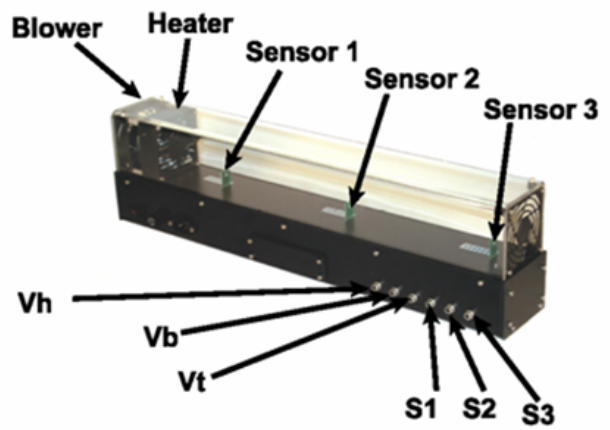


Figure 4.20: The heatflow apparatus.

to the human eye. This means that creativity in the development of the user interface is a key issue. We will therefore see how *Ejs* facilitates the work involved by using the predefined graphical elements of the *view*.

4.3.1 System overview

The plant consists of a duct containing the following components: a heating element and a blower located at one end of the structure and three temperature sensors S_1, S_2, and S_3 located along the duct. Power delivered to the heater is regulated using an analog signal. The fan speed can also be controlled with an analog signal (the fan speed is measured using a tachometer). Fast settling platinum temperature transducers are used to measure the temperature.

We have to bear into account that temperature sensors located inside the structure will perceive the effect of the heater according to the distance between the energy suppliers and the sensors. Figure 4.21 shows a lateral view of the system illustrating this idea. The modelling and control of this process is addressed in Appendix A.3 and no additional information is given here. This chapter will only focus on how to create web-based control labs using the software tools and approaches suggested in this dissertation.

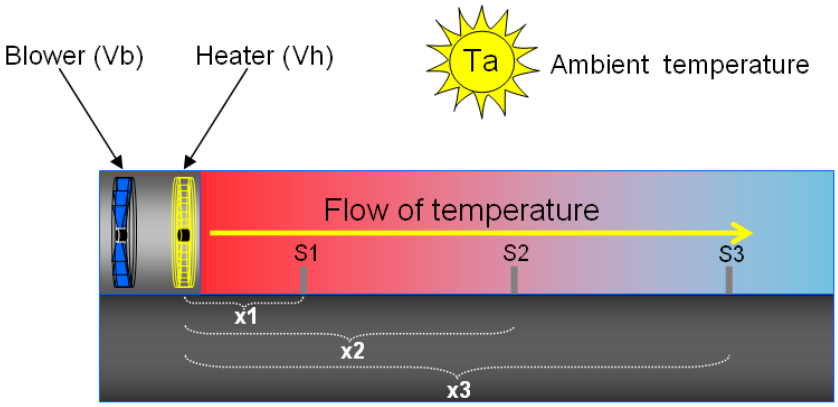


Figure 4.21: Variables of the apparatus.

The setup of the server side applications is described hereafter. Again, this section focuses mainly on the development of the local control VI, since issues of communication have already been tackled in the three-tank prototype (JiL server) and in the previous chapter.

4.3.2 Local control of the heatflow system

The LabVIEW VI developed is shown in Figures 4.22 and 4.23. A sequence structure was used to program the local control with hardware in the loop (see Figure 4.23). This VI controls the hardware of the thermal process based on the structure described in Figure 3.28 (Section 3.3.5). The application was developed so that users can switch between manual or automatic mode. When working in automatic mode the user can choose between one of the three sensors to close the loop. It is also possible to tune the parameters of the PID controller on-the-fly or change the temperature setpoint in the sensor used to close the loop. As was the case for the three-tank prototype, a resetting code is executed when the variable labelled as *stop* is pushed (see Figure 4.22).

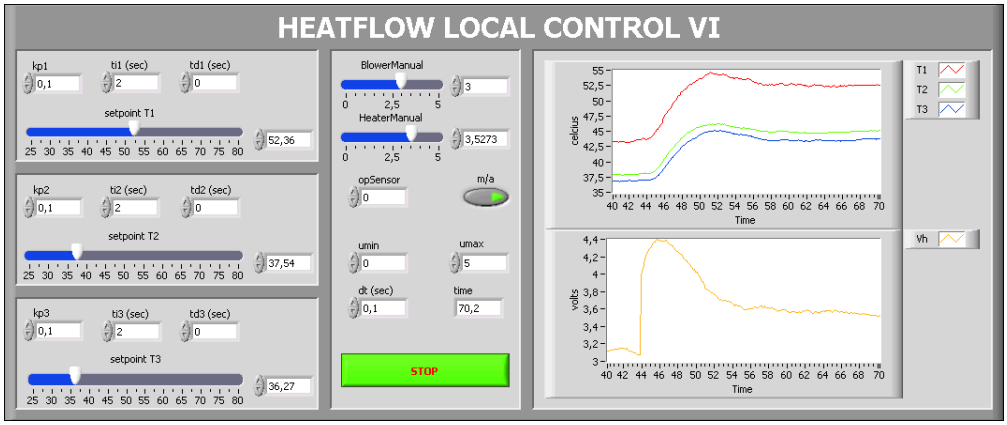


Figure 4.22: Local control of the heatflow real system - Front panel.

Making the VI available on the Internet means that only the JiL server is required to run and move the *heatflowReal.vi* file to the *apps* folder. One should mention that no specific communication facilities have to be included in the VI.

4.3.3 The virtual and remote laboratory

Figures 4.24 and 4.25 show the views of the simulation created with *Ejs*. The first one (see Figure 4.24(a)) depicts the interface of the laboratory when working in simulation mode, that is, using the mathematical model programmed in *Ejs* with its ODEs editor. The 3D graphical representation of the process was built by faithfully reproducing the shape of the apparatus.

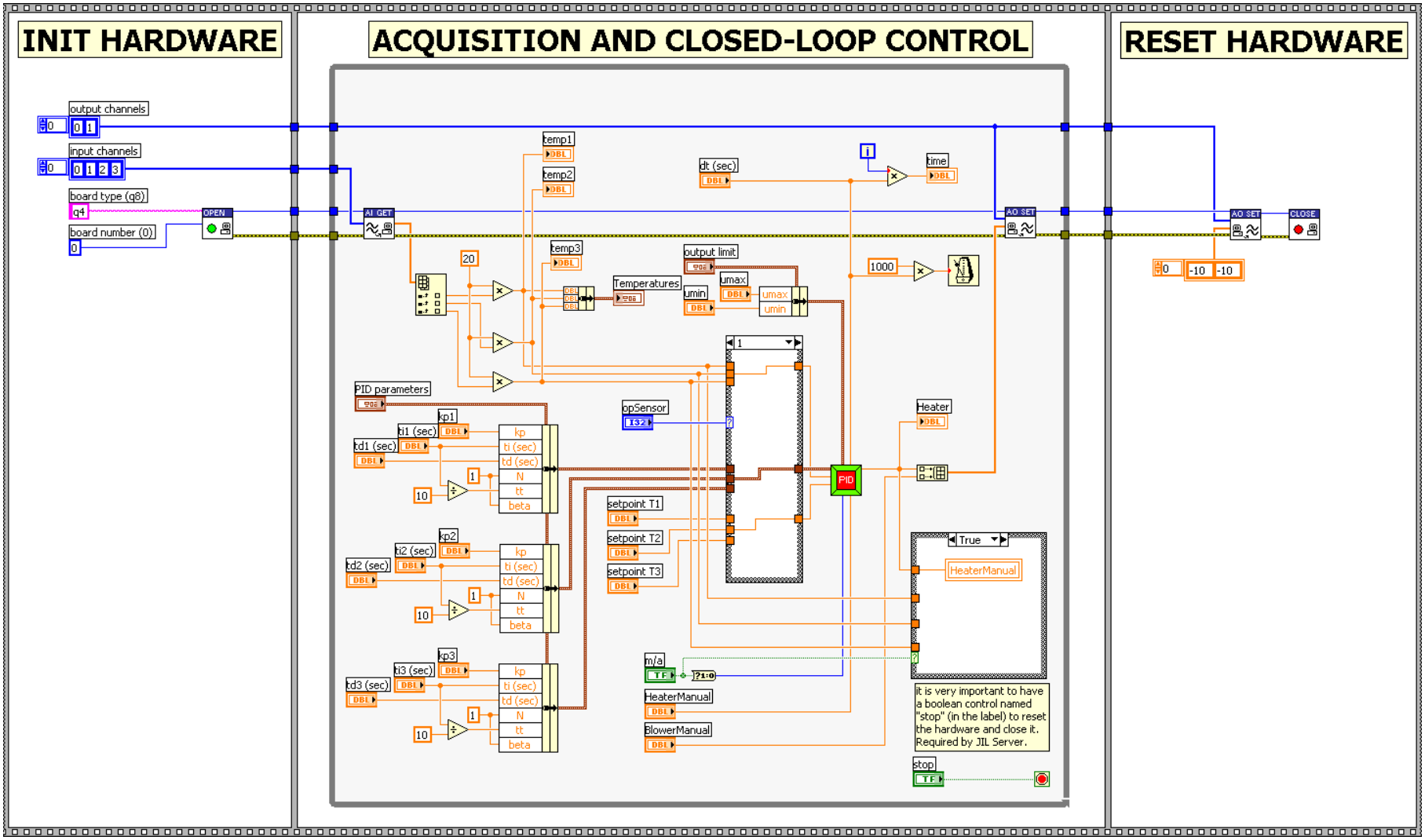
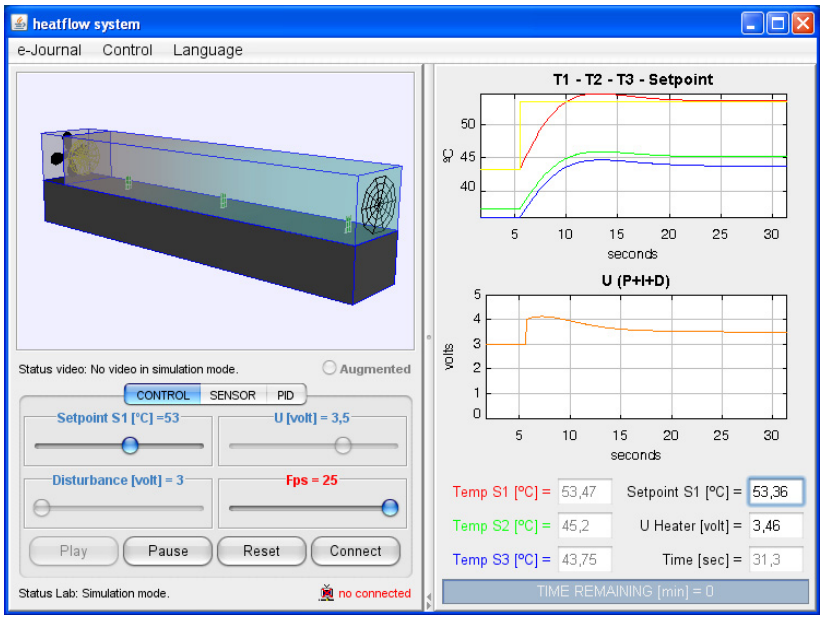
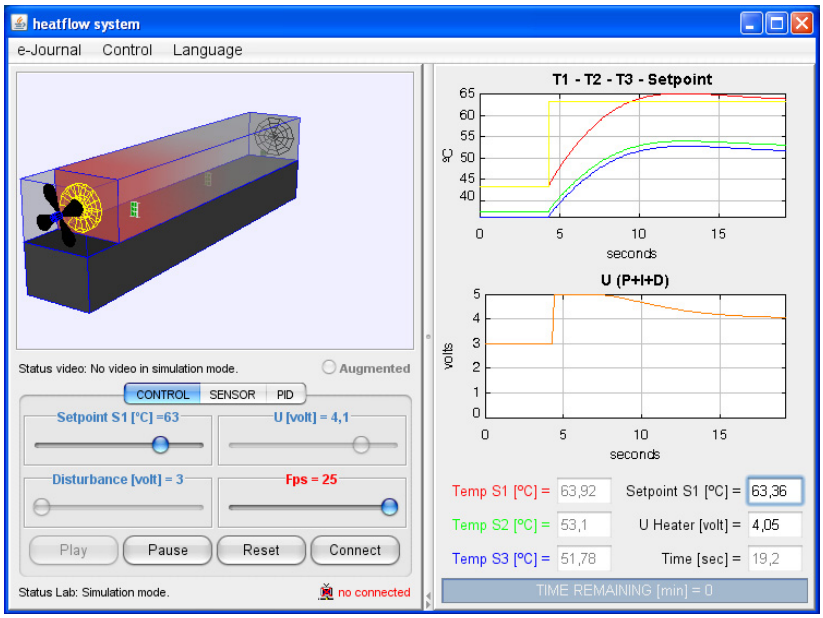


Figure 4.23: Local control of the heatflow real system - Block diagram.

The tridimentional representation of the apparatus provides more realism when working in simulation mode thus allowing students to gain a better insight of the process. Users can interact directly with this *view*, for instance, by moving the apparatus around its centroide and obtaining different perspectives of the structure (see Figure 4.24(b)). Heater and blower have also been represented at the end of the apparatus. The color of the heater changes and the blower turns around its axis according to voltage applied.



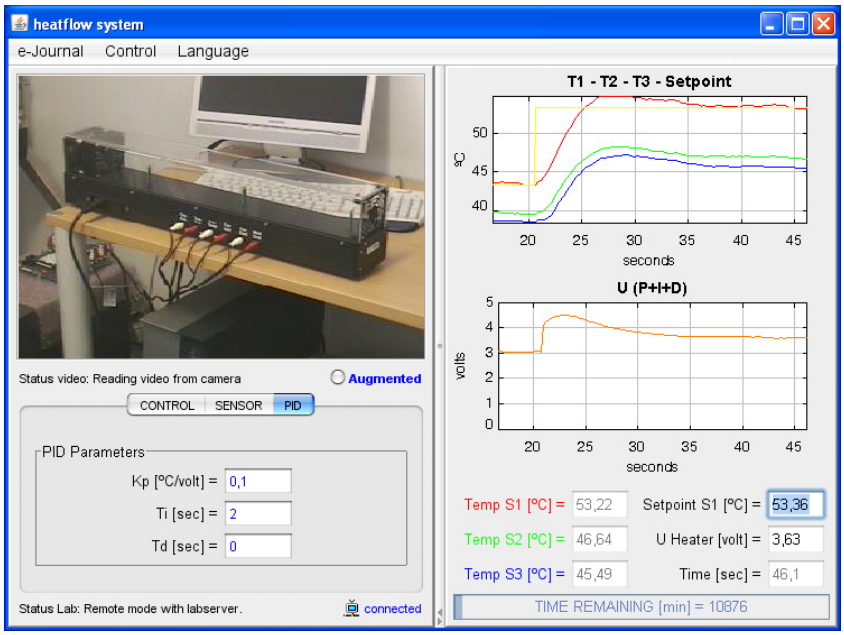
(a) Final GUI in simulation mode.



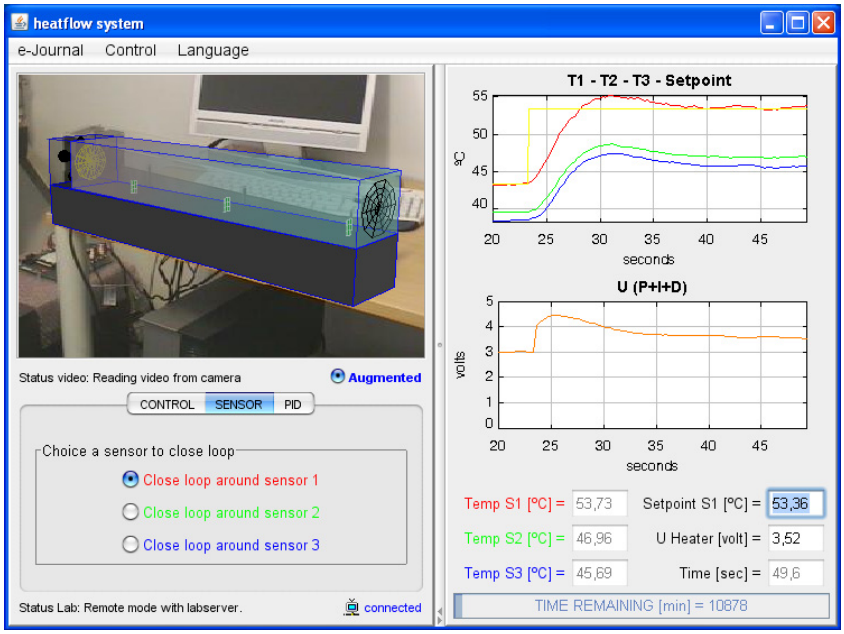
(b) Another 3D perspective of the view.

Figure 4.24: The web-based laboratory of the heatflow system in virtual mode.

Three small vertical rectangles placed along the 3D representation simulate the sensors and the color inside the duct (3D cube covering the sensors) represents the air temperature. A **WebCamImage** element displaying the output of a web-cam (see Figure 4.25(a)) was also added to the *view*. Since the air heating process is not visible to the human eye, the video image is enhanced with a coloured 3D image representing the air temperature.



(a) Remote mode with video feedback.



(b) Remote mode with video and the augmented reality option.

Figure 4.25: The web-based laboratory of the heatflow system in remote mode.

Video images can then be visualized in the background of the 3D representation resulting in a very pleasant augmented reality effect (see Figure 4.25(b)). Students' perception is increased as they can actually observe the temperature flow effect inside the structure. ➠ The results of this study were published in (Vargas et al. 2006a,b).

4.4 Prototype III: The DC Motor

The DC motor is one of the classical experiments in automatic control laboratories. It allows to study the dynamic behaviour with regards to the *speed* and *position* of a motor fed by a direct current source. The DC motor is a common actuator in control systems and requires therefore, although this is a simple and straightforward example, special attention given its contribution in the field of education. Figure 4.26 shows the didactical equipment used and its hardware components. ➠ Results were published in (Vargas et al. 2008).

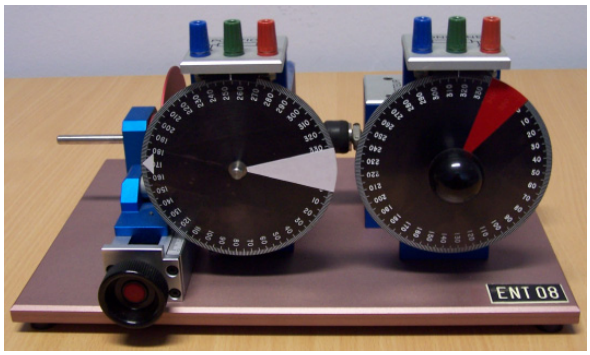


Figure 4.26: The Direct Current Motor didactical equipment used in the laboratory.

4.4.1 System overview

The didactical equipment is an electromechanical process intended to perform the angular position or velocity control of a load using the direct current supplied to the motor (see Figure 4.27).

The load is composed of an inertia (steel disk fixed to the motor's axis) and a viscous friction provided by a magnetic brake. The engine is fed through a unity gain amplifier capable of delivering the power required to the motor.

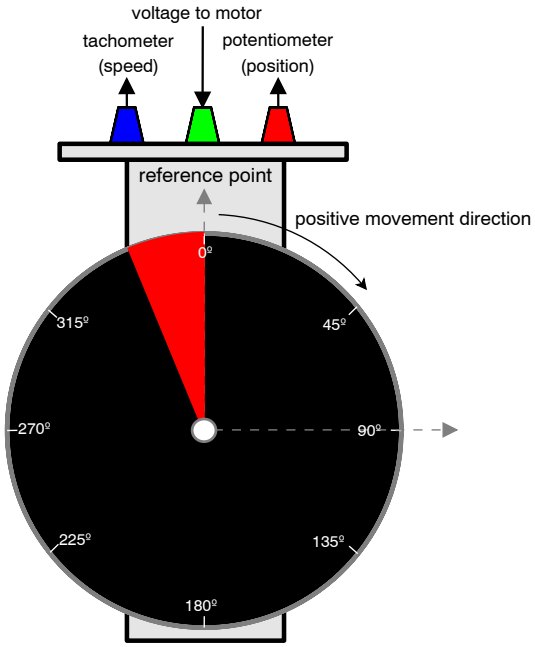


Figure 4.27: The DC motor scheme.

A tachometer provides voltage u_w in proportion with the angular velocity of the load. A potentiometer with a reducer device provides a voltage u_θ proportional to its angular position. A similar potentiometer is also available to change the reference y_c directly in the equipment.

The modelling and control of this process is addressed in Appendix A.2 and no additional information is given here. As with previous prototypes, this chapter pretends to further tackle the creation of web-based control laboratories using the software tools and approaches provided in this dissertation.

4.4.2 Local control of the DC Motor

The intrinsic *time constant* of this mechatronic device defines a challenging problem because of the fact that is almost in the same order of magnitude as the Internet transmission time. Again, the JiL server approach provides a lot of help in the case of these applications by separating the server program in a communication generic module (without real-time constraints given that communication functions are inherently non deterministic by existing delays in the network) and the closed-loop control module (whereby real-time execution must be guaranteed). In this case, a local control VI could be created using some of

the technological alternatives that National Instruments provides to LabVIEW users to develop applications with real-time restrictions (for example, NI-DAQ with dedicated processor to real-time tasks whereby the local control VI can be embedded into card itself, or any other more robust solutions).

Figures 4.28 and 4.29 show the application *motorReal.vi* that locally controls the DC motor. The sampling period used in the control loop is 20 [ms] (*Input Rate* of 50 [Hz] in **Timing & Triggering Parameters** of the Front Panel).

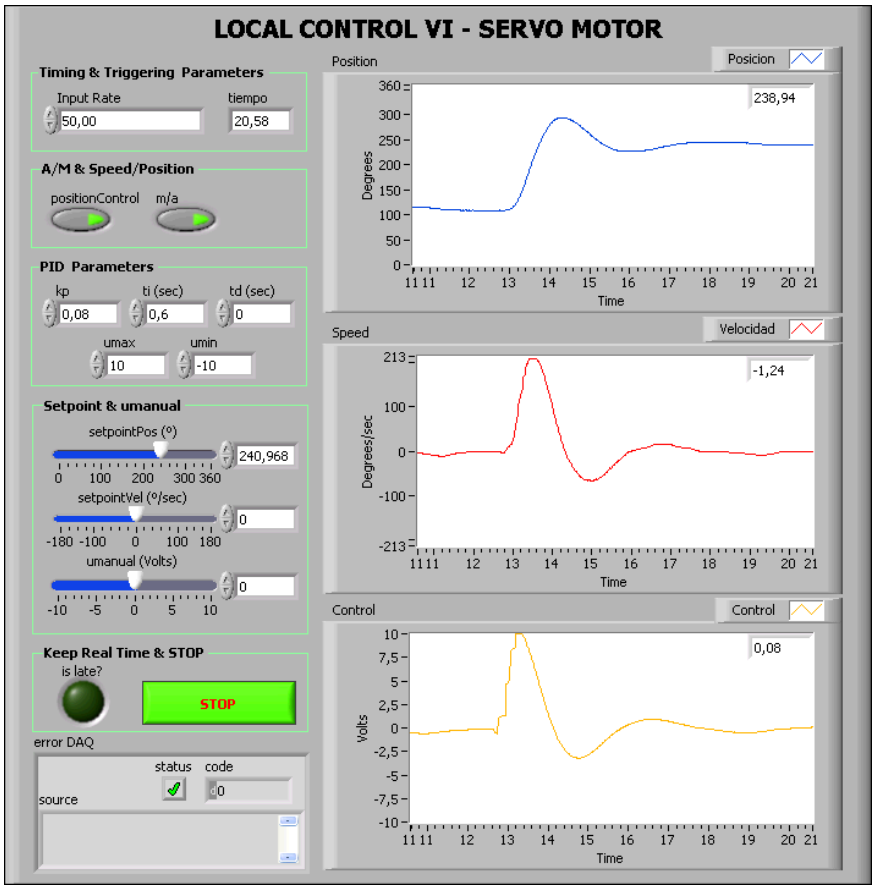


Figure 4.28: Local control of the DC motor real system - Front panel.

To avoid overflow in the communication channel due to the delivering of data packets to the client, the JiL server is configured to send data every 100 [ms], that is, the control task runs at a rate of 20 [ms] but the JiL server retrieves and sends the client details of the state of the motor every 5 steps of evolution in the real-time control task. Although some data are lost, this sending rate is high enough to fluently observe the dynamic behaviour of the process in the client interface (see Figure 4.30).

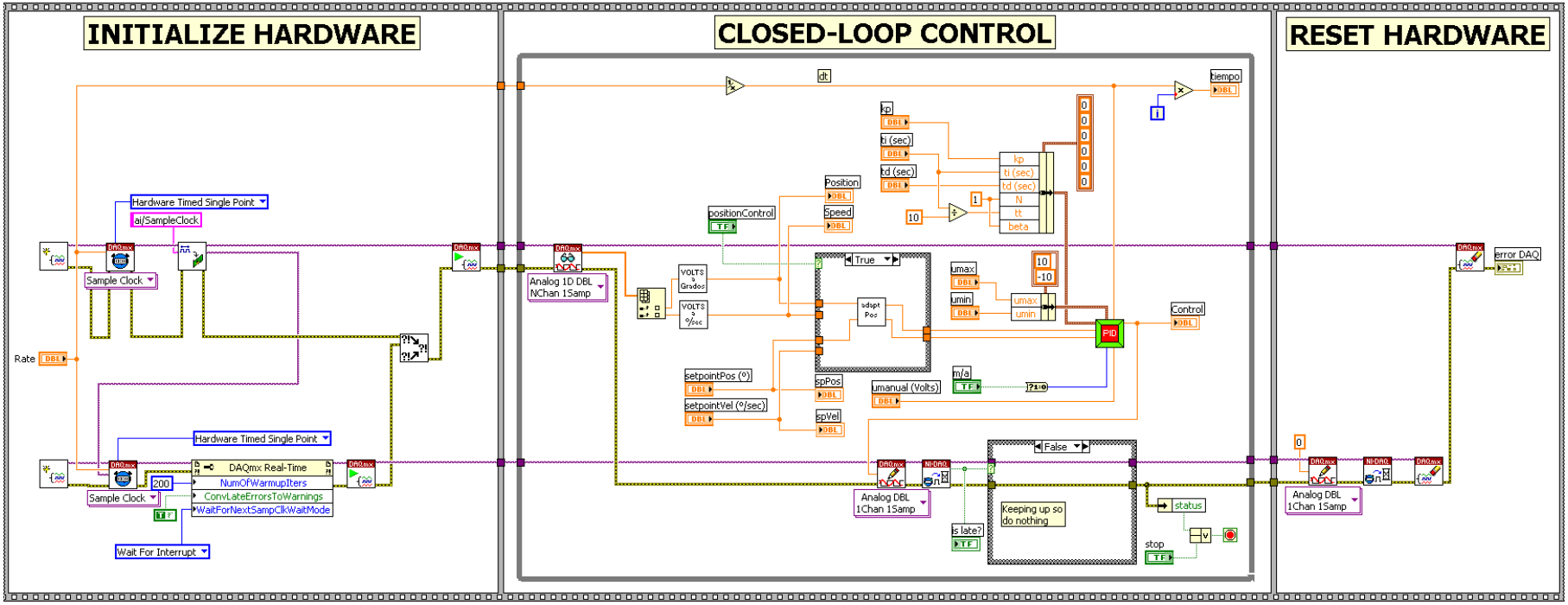


Figure 4.29: Local control of the DC motor real system - Block diagram.

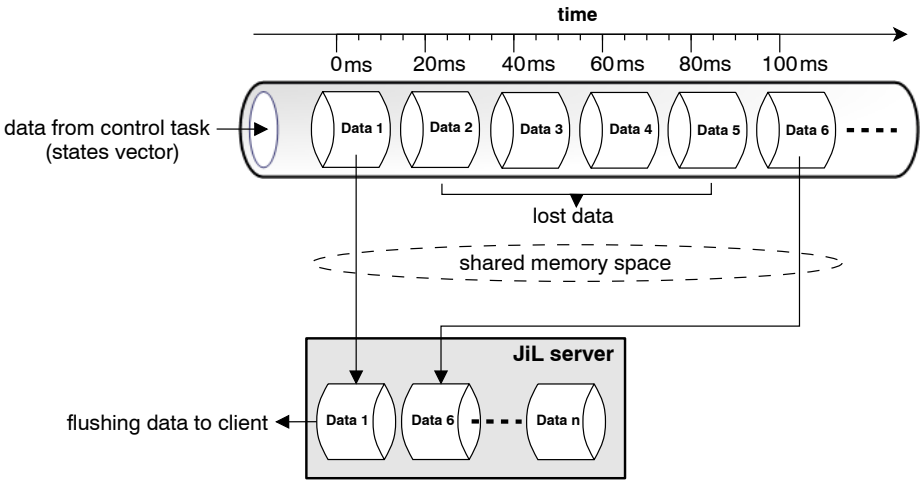


Figure 4.30: Operations of the JiL server when sending data to a client.

The **A/M & Speed/Position** area of the Front Panel contains two boolean buttons, *positionControl* and *m/a*. When pushing the first button, users can choose between working on either position or on the speed control of the disk. The second button allows to switch between manual or automatic control mode. The box **PID Parameters** of the GUI allows to configure the value of the controller parameters K_p, T_i and T_d and the actuator saturation limits (*umax* and *umin*).

The **Setpoint & umanual** options allow the users to interactively change the setpoint value and, at the same time, modify the voltage applied to the motor in manual mode. In the **Keep Real Time & STOP** area, a *circular-shaped led* indicates whether real-time constraints are kept in every iteration of the loop, and a variable named *stop* handles the stopping of the VI target in a controlled way. Finally, three *waveform chart* components display the temporal evolution of the system. The first one plots the *position* (in degrees) of the motor, the second one shows its behaviour in *speed* (in degrees/sec), and the third one depicts the *control signal* applied to the motor (in volts).

The following sections describe the final virtual and remote control laboratory used by the students to carry out the experimental sessions across the Internet. The interface created with *Ejs* allows for the handling of the VI through the predefined view graphical elements of *Ejs*, that is, all the functionality of the VI is replicated in the client application by *Ejs*.

4.4.3 The virtual and remote laboratory

Figures 4.31 and 4.32 show the four main views of the web-based laboratory of the DC motor created with *Ejs*. One can see that the position in the interface of the graphical element is again quite similar to the previous prototypes mentioned. This means, the usability of the applications is enhanced. Students can observe a similar structure in every laboratory thus learning time to understand and assimilate interface options available when they move from one laboratory prototype to another is therefore reduced.

Visualization and control options of the interface are described below:

Menu options

Through this menu (upper part of the interface), users can choose the language of the interface (Spanish or English), the control mode (manual or automatic), and, finally, are able to save data registers obtained during a working session by using the *eJournal* options available.

Graphical representation of the DC motor

The rotational movement of the steel disk is reproduced by a copy of this component (a photo of the disk). This image provides the same visualization effect when working in either simulation or remote mode.

Control panel of the laboratory

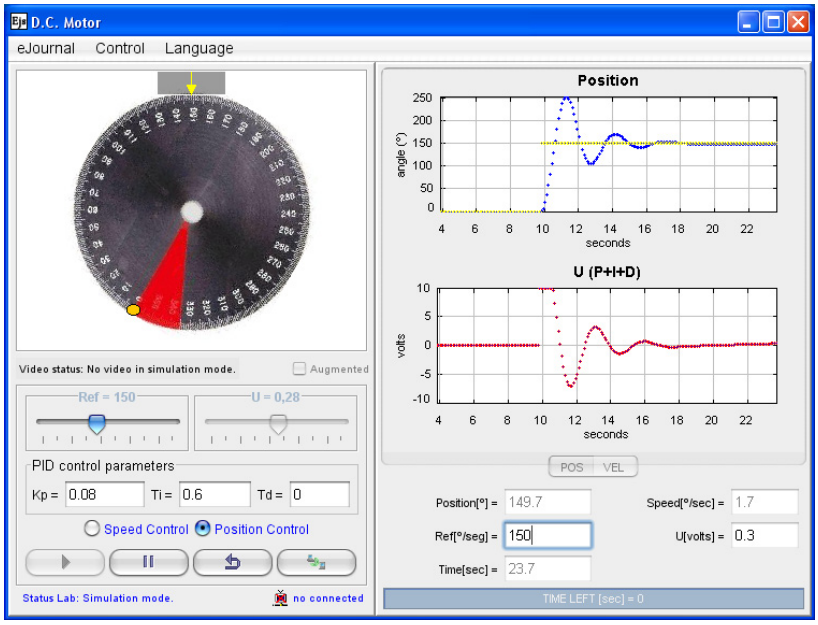
A set of graphical components to control the dynamic behaviour of the motor is located under the process scheme. Users can choose between position or speed control (see Figures 4.31(a) and 4.31(b)). They can also set both the setpoint value in closed-loop control and the manual voltage applied to the motor when working in open-loop. Three numerical fields allow to change the parameters of the PID controller on-the-fly. Four buttons allow the users to *play*, *pause* or *reset* the simulation of the process when working in virtual mode. The latter allows connection to the real plant to work in remote mode. Some text fields are also added in the upper and lower part of the control panel to display *connection state messages*.

Plotting panels

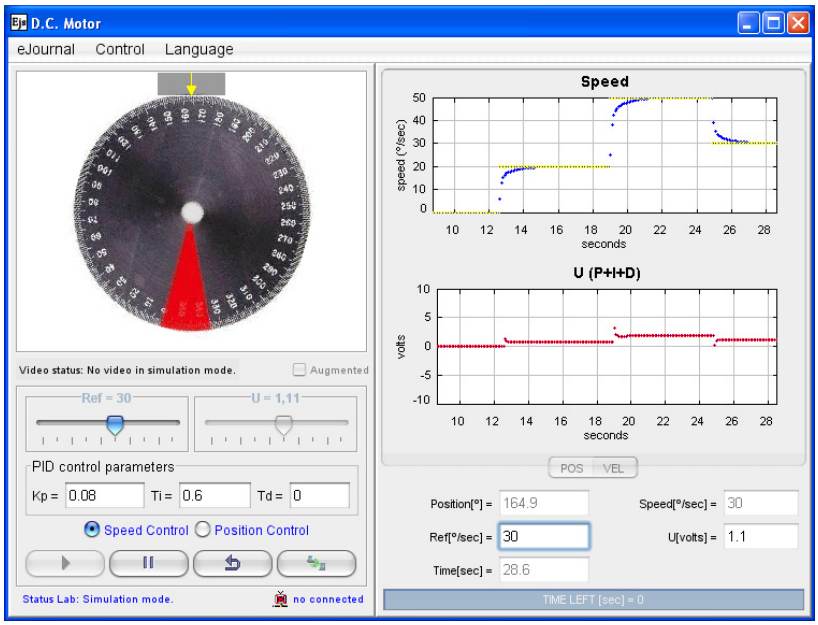
On the right side, two signal scopes show the temporal evolution of the main signals (speed, position, reference and manipulated variables).

Indicators panel of instantaneous values

At the bottom-right corner of the interface a set of numerical fields display the current value of the system variables.



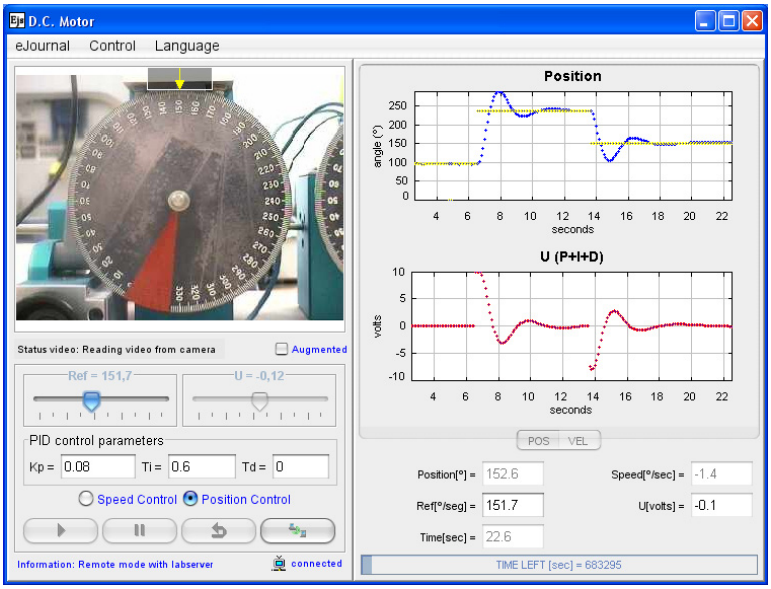
(a) Simulation mode in position control.



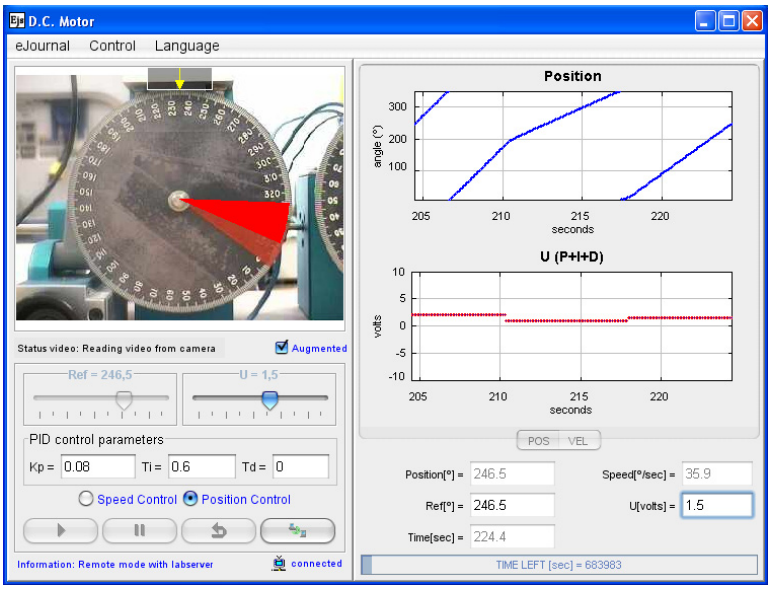
(b) Simulation mode in speed control.

Figure 4.31: The web-based laboratory of the DC motor in virtual mode.

Figure 4.32(a) depicts the DC Motor interface working in remote mode with visual feedback. The steel disk is graduated in degrees to visually check the correct position of the load. A polygon element of the *Ejs* graphical library is used to enrich the visualization of the system. This polygon has the same shape as the red sector that shows the position on the steel disk. If we look at this element, we can see the lag between video images and the augmented view is due to the fact that incoming data are coming from two different sources, the IP camera and the computer connected to the real plant (see Figure 4.32(b)).



(a) Remote mode with video feedback.



(b) Remote mode using augmented reality.

Figure 4.32: The web-based laboratory of the DC motor in remote mode.

So far, we have described three real examples for which we applied the suggested methodology, step by step, in order to develop web-based laboratories designed for pedagogical purposes. As mentioned at the beginning of the chapter, these prototypes are part of the current infrastructure of laboratories that the *Department of Computer Science and Automatic Control* of the UNED provides students for remote experimentation. For this reason, the three prototypes were fully tested using performance and usability criteria.

4.5 Conclusions

The analysis, design, and building of three real prototypes of virtual and remote control labs to perform practical experiments through the Internet have been described in detail. The benefits of using the *JiL server approach* to create web-based control labs using Java (for the client-side) and LabVIEW (for the server-side) have been shown successfully. The developing time needed in the case of a new remote experimentation environment using both software technologies has been reduced. The creation of a generic communication module independent from the control task makes the system more reliable and easy to maintain.

From a client perspective, each example is a novelty in terms of its development. The *three-tank MIMO system* presents several interface configuration options in virtual mode. The *heatflow system* has a very pleasing visualization effect that shows the graphic design possibilities that *Ejs* provides. Finally, the *DC motor system* describes how to deal with the remote control of didactical plants with fast dynamics and real-time constraints. One should highligth the high degree of interactivity that these applications developed with *Ejs* provide compared to previously recorded applications. Students can understand all the intuitive and strategical aspects of the models suggested via simple interactions with the interface (sliders, buttons, checkboxes, etc...) or even directly over the *view* of the process itself (virtual representation of the process).

5

The e-Learning Layer

Overview

So far, the various aspects related to the building of virtual and remote experimentation labs have been analized and described through three practical examples. However, these experimental applications do not fully cover all the current requirements of the conventional face-to-face experimental sessions.

In a conventional laboratory, students can interact with others, ask questions to the teacher, take notes about the work carried out, save data registers of their experiments, compare and contrast results with other class mates, etc. This chapter provides a detailed analysis of how this problem was addressed in this thesis.

The pedagogical aspects to take into account in remote experimentation are mentioned first. In this sense, a global vision of the features that a flexible learning environment should provide to effectively support a community of practices in a distributed scenario is presented. Finally, the approach chosen to address the on-line learning of students in control engineering education will be described.

5.1 On-line learning: Pedagogical aspects

The potential of web-based experimental applications used as pedagogical support tools in control engineering education has already been described in previous chapters. By using these tools, engineering students can be required to complete different tasks and/or activities during experimentation sessions. However, these activities must be carefully designed so that they avoid inherent drawbacks that exist when carrying out distant experiments. In this particular case, students must conduct their practical assignments without the help of an "on-site" instructor. Therefore, additional tools are required for virtual and remote control laboratories so as to:

- Provide all the neccesary documentation to carry out a complete remote practical session.
- Provide a common workspace where instructors and students (or students only) can interact, synchronously or asynchronously, in a similar way than in traditional labs.
- To give the possibility to create workgroups where users can collaborate and interact among them such as they would do it in a face to face class.

To address this problem, complementary web-based resources should be explored for a convenient use of web-based labs.

As mentioned in the introduction of this dissertation, the *flexible learning paradigm* is presented as an appropriate solution for the on-line teaching of engineering students. This paradigm can be applied taking into account the three following perspectives:

- *Pedagogical*: From this perspective, flexible education means that students are given extended access to learning resources, increased freedom to organize their learning activities, and enhanced participation, autonomy, and collaboration.

- *Technological*: From this perspective, flexible education enables adequate exploitation of information and communication devices as well as infraestructures, especially the Internet.
- *Organizational*: From this point of view, flexible education relies on renewed study programs, regulations, as well as partnerships and collaborations with other institutions.

These three points of view on the flexible education paradigm have already been addressed throughout the analysis, design and development of the present thesis. In fact, the UNED being a distance learning university, the application of such teaching alternative modalities is the main goal for this academic institution and therefore, big efforts are always made to pursue such objective.

Pedagogical aspects should be addressed first since the quality of teaching must be maintained when providing remote experimentation services in an open academic environment. As there are different learning models available (Maharg 2004), there is more than one possible approach to e-learning and e-teaching:

- ✍ **Student-centred learning**
- ✍ **Blended learning**
- ✍ **Social learning**

The *student-centred learning methodology* aims at designing learning tasks from the standpoint of students with a clearly defined sequence of actions instead of a learning process that places full responsibility on the students themselves (Kurhila et al. 2004). This learning style relies on the effective arrangements of three different elements: *show-tell-do*. The results obtained of an "X" task set to students (SHOW) could be used as an example of this learning method. The experiment conducted will then be explained using some keywords (TELL). And finally, a research task for students to complete by themselves (DO) will be set. This is a common learning rule for face to face laboratory sessions. However, if this learning method is applied in the case of virtual and remote labs, students can benefit from flexible time and space and could even get instant feedback.

The *blended learning methodology* is understood as a combination of self-led learning and other learning resources (live seminars or workshops), with the possibility of forming workgroups. Live seminars allow students to get a first insight into the contents of a lesson. This will help them confirm that they understand the subject prior to discussing it in group. This will, therefore, encourage them to come properly prepared so as to contribute actively. In other words, all participants should feel that they are members of a group, that they are not working in isolation and without support, especially in the case of courses involving high-tech contents.

The *social learning methodology* provides slightly more than the blended learning method. In particular, in addition to the necessity of being part of a group, it provides the opportunity to meet with a teacher. In fact, the presence of the role of teacher or "tutor" enhances students' motivation the same as in a traditional class with a leader and an formal objective.

In (Anderson & Elloumi 2004) one can find a general model of how teacher

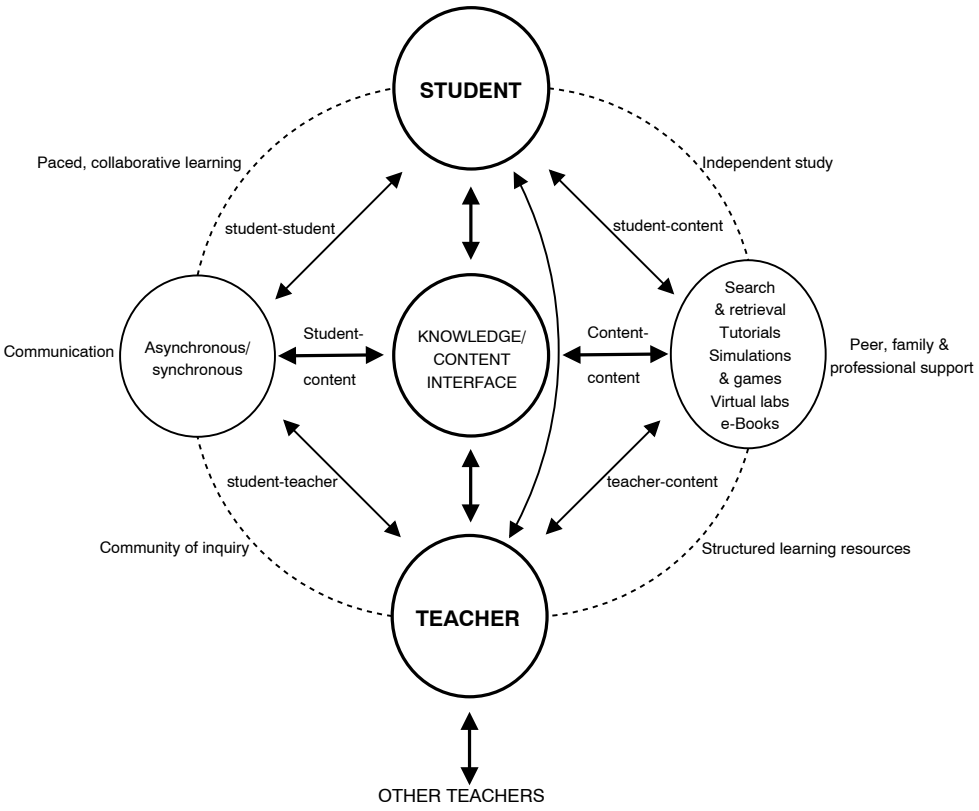


Figure 5.1: Interaction model illustrating the two main modes of on-line learning.

and student interact with one another and with the contents of a course. Figure 5.1 shows such interaction model illustrated with communication links between the different model components.

As a summary, and in order to introduce UNED control engineering students an appropriate learning model, the concepts mentioned in the case of third methodology were adopted. The solution relies on the use of eMersion (Gillet & Fakas 2001, Gillet et al. 2005, Nguyen 2006), a web-based application which, somehow, implements a *social learning model* focusing on the on-line teaching of students in subjects with a high technical content. The following section presents the advantages of this software tool in the context of remote experimentation.

5.2 eMersion: A novel approach from EPFL

5.2.1 Introduction

The implementation of the *e-Learning Layer* is based on eMersion, a web-based experimentation environment created by the research group **ReAct** (Real-Time Coordination and Sustainable Interaction System Group (React 2009)) from the Automatic Control Laboratory of EPFL, Switzerland. Remembering the words of the developers in (Gillet et al. 2003), to explain how the eMersion environment was conceived, the authors state the following:

> "*Carrying out web-based experimentation is a matter of observing and acting on a virtual model or on a real equipment using convenient visualization and control devices. Hence, a student enrolled in such activities can be seen as a pilot siting in the cockpit of an exploration vehicle to complete a mission. In a web-based experimentation framework, the given mission is tipically a laboratory assignment and the cockpit is a computer. To take advantage of this similarity, a general cockpit metaphor has been chosen at the EPFL to design the graphical user interface (GUI) of the environment dedicated to web-based experimentation*".

From a *design* point of view, eMersion meets the majority of requirements for web-based experimentation environments. A complete review of the main characteristics of collaborative hands-on activities in such learning environments is presented in (Nguyen 2007). A summary of these essential features is provided below:

Hands-On activities Support. Virtual and remote labs should support hands-on activities. Such resources are paramount in engineering curricula since students need to have contact with mechanisms taught and materials used.

Component Integration. Additional web-based resources should be integrated into the same experimentation environment so as to support hands-on activities. Experimentation by itself, interaction and collaboration support as well as, complementary information for experimentation process are some examples of these additional web-based resources.

Multi-session Experiment. The system should allow to experiment in a flexible way, i.e., students could complete tasks set at anytime and from any location. In addition, the system should also allow several trial and error experiments to reinforce students' understanding.

Types of Collaboration. The system should place a greater learning responsability onto the students. Different collaboration mechanisms could help reinforce this idea as these interaction resources would encourage collaboration between peers and tutors and allow them to become active agents.

Discretionary of Collaboration. Collaboration and interaction should not be mandatory. The system should allow students to switch between a single and a collaborative working mode in a transparent way.

From a *handling* point of view, the previous quotation describes this environment as a space in which the students can find all the means necessary to carry out on-line laboratory assignments in a flexible learning context. The graphical user interface of eMersion allows to surf across the experimentation environment such

as a pilot would do in an aircraft cockpit. Hands-on activities are conducted online using either simulators (virtual-labs) or remote connections to real laboratory equipment (remote-labs). Typical experimental sessions are mediated by teachers and/or tutors emulating hands-on activities carried out in the face-to-face learning modality. Furthermore, student/student interaction and collaboration is also encouraged by means of a shared workspace where they actively create their own contextual meaning, rather than passively acquiring knowledge structures created by other actors in play (Nguyen et al. 2006).

5.2.2 Web technology behind eMersion

The selection of an appropriate web technology to develop web-based environments is of great importance. In fact, many alternatives are available for such a purpose (PHP 2009, Visual.NET 2008, AJAX 2009). However, choosing which the most convenient is not an easy task. Although this dissertation does not deal with the low-level development of eMersion but actually just uses it, some information regarding the web technology underlying this web-based experimentation environment is provided hereafter.

Jakarta struts framework

eMersion was built using the framework Struts used to build web applications. Struts[1] is an open source framework that helps develop web applications based on the Model-View-Controller (MVC) design paradigm (Cavaness 2005). The *Model* represents the business logic or database code, the *View* represents the page design code, and the *Controller* represents the navigational code. Struts puts Java servlets[2], Java Server Pages[3] (JSP), custom tags, and messaging resources together into a unified framework and saves the developer the time of coding a complete MVC model (Nguyen 2006). Figure 5.2 shows the request/answer mechanism of Struts. User actions are intercepted by a *servlet controller* that processes the requests. If the request implies dynamic processing in the server, as

[1] http://struts.apache.org
[2] http://java.sun.com/products/servlet/reference/index.html
[3] http://java.sun.com/products/jsp/

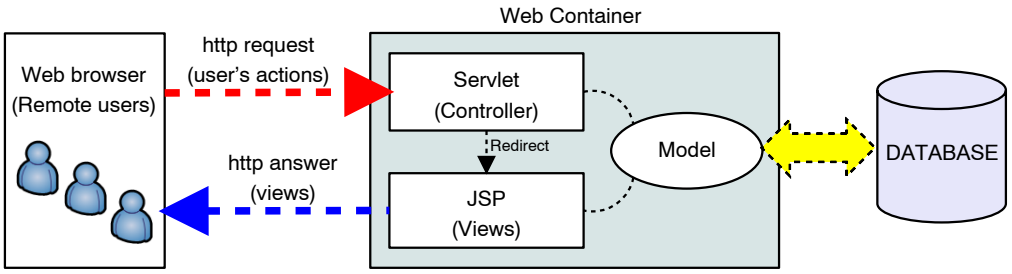


Figure 5.2: Struts framework. Flow of information (request/answer).

for instance, a query to a database, the servlet controller links with the *model* of the application to get the result. Then, once the request has been executed, a *jsp view* is generated based on the information previously obtained. Finally, the view is sent to the client who visualizes the answer, thus closing the request/response loop.

Struts integrates other developments making it one of the better known and used frameworks to build web applications (Apache-Validator 2009, Apache-Logging 2009, Apache-Pool 2009, Apache-Tiles 2009).

5.2.3 eMersion abstractions and concepts

We have already mentioned that eMersion is a web application that focuses on the teaching and learning of students in subjects with a high-tech content. It specifically supports hands-on activities carried out with students through the Internet in a flexible context. In this sense, the eMersion architecture involves some abstractions and concepts which can be found in a university from an organizational point of view. The structure of the environment suggests a first global view of the system. Figure 5.3 depicts this first level of abstraction as a starting point of the eMersion architecture. Concepts presented can be summarized in the following three points:

- A university disposes of *laboratories*
- Each laboratory has a *professor* and most likely *tutors*
- Students attend *courses* taught by professors

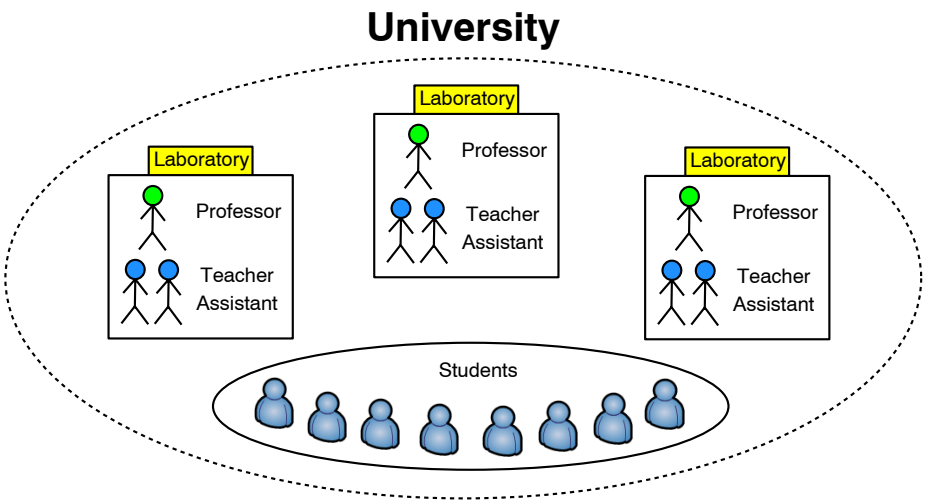


Figure 5.3: General abstractions representing the eMersion organization.

These three key points are the centerpiece in the case of the eMersion design. In fact, every piece of the environment is built in order to represent each of these concepts. Hence, the following lines describe how these ideas were introduced in the development of this web-based experimentation environment.

eMersion disposes of a first level of administration (see Figure 5.4). A "super user" or *Global administrator* manages the system. This user can create ***Spaces***

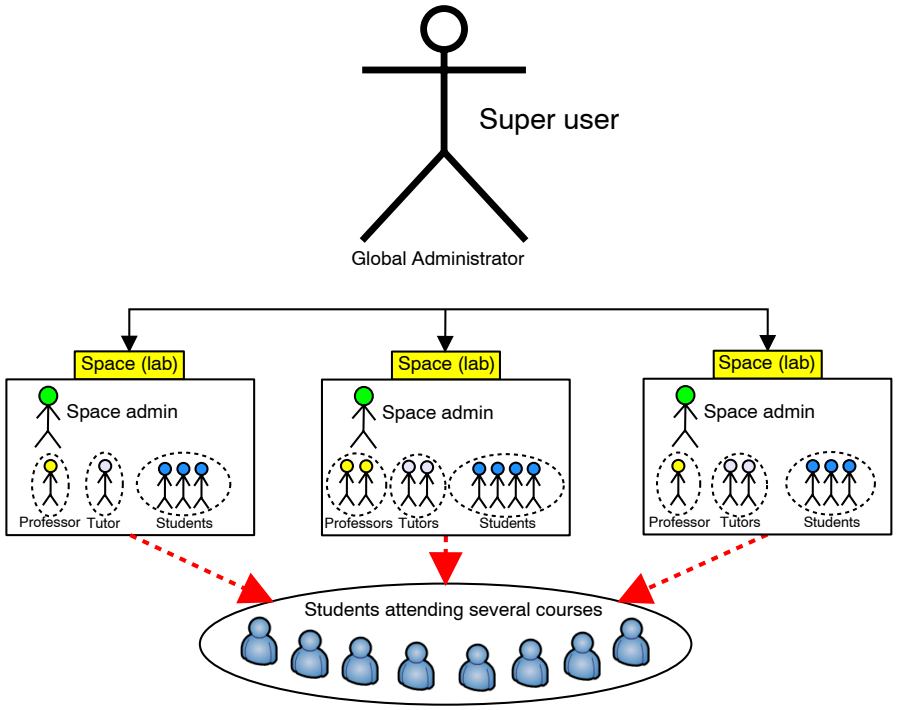


Figure 5.4: First level of abstraction in eMersion.

which could be seen as an organizational unit of a university, as for example, a department. When the *Global administrator* creates a space, a *Space administrator* is automatically created. The internal composition of a *space* would correspond to a second level of abstraction of eMersion. A space administrator can create ***Courses*** to which groups of teachers, tutors and/or students can be associated (see Figure 5.5). It is important to notice that students could attend courses coming from different spaces.

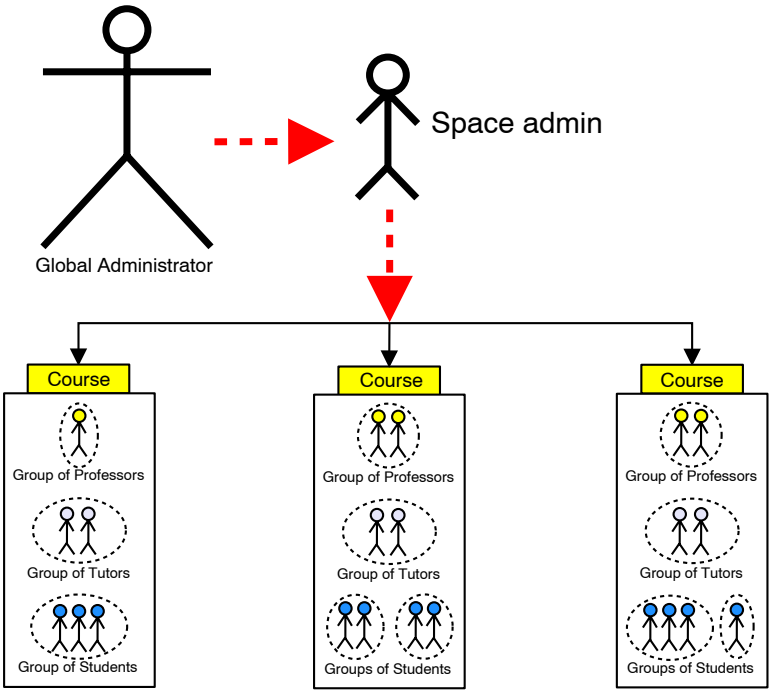


Figure 5.5: Second level of abstraction in eMersion.

The third and last level of abstraction corresponds to the ***Modules*** created by a *Course administrador* or *professor*. A module can be seen as a laboratory used for a course. Several modules (or laboratories) can be associated to a *course* in a similar way as occurs in any engineering course, where one or more laboratory sessions are carried out to explain different concepts. Figure 5.6 depicts the ideas above mentioned. As we can see, the professor administrator of a course can manage several modules. Each module can have one or several groups of students aiming at completing their laboratory assignments using the graphical user interface of eMersion, this being the last branch of the tree to configure.

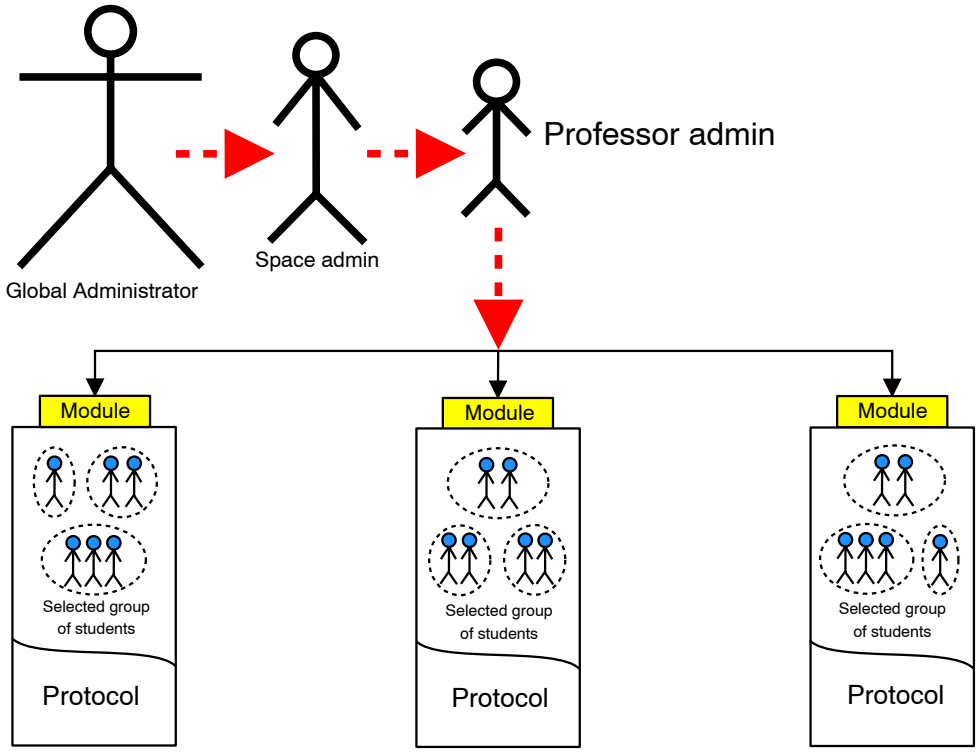


Figure 5.6: Third level of abstraction in eMersion.

The organizational structure of the web-based experimentation environment used in this dissertation to implement the *e-Learning Layer* has now been exposed. The following sections describe the graphical user interface of eMersion, that is, the look and feel of the web environment and the functionality of each of their components.

5.2.4 Functional architecture of the eMersion GUI

The eMersion GUI is composed of a set of independent web applications that make up the entire environment. Figure 5.7 shows each component of the eMersion GUI. Of all these modules, the *eJournal* is highlighted as it implements a big part of the interaction and collaboration services provided by eMersion. A student enters the environment via a web browser. Once authenticated, a set of pop-up windows are automatically opened to display the entire experimentation system. In Figure 5.7, each window represents a web-module developing a specific task into a client web browser.

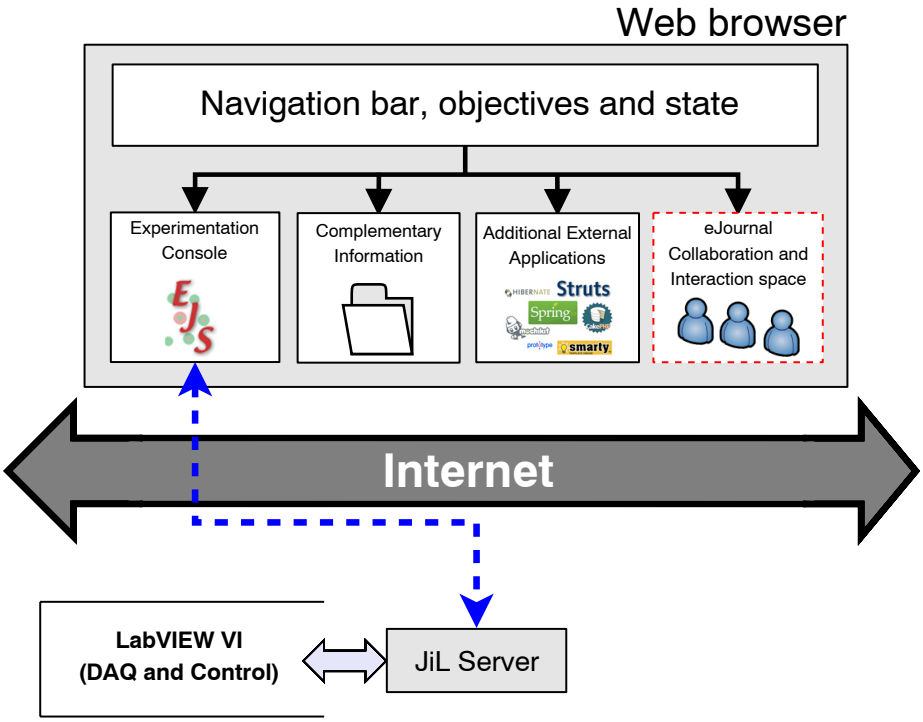


Figure 5.7: Functional structure of eMersion.

A brief description of each component of the collaborative web-based experimentation environment "eMersion" is detailed as follows:

Navigation bar

Figure 5.8 shows the look of the web-component *navigation bar*. The window is divided into four main areas: *Objective*, *Navigation*, *Current Task*, and *Awareness*. The first contains a description of the learning objectives pursued by *course modules*. The second one covers a set of icons to enable the user to access the different modules that compose the system. The third contains an indicator showing the current task carried out by the user and a link to the *Access Protocol*, a document describing how to handle the environment. The fourth area contains additional web-components.

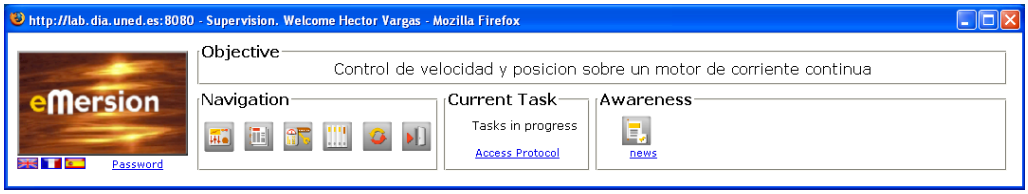


Figure 5.8: The Navigation bar allows access to the web modules of eMersion.

Experimentation console

The so-called *experimentation console* web-component contains the applet Java generated by *Ejs* following the development scheme suggested in the *Experimentation Layer* (Chapters 3 and 4). Students can conduct laboratory assignments as well as in a traditional lab, that is, running control experiments using a simulation of the target process (*virtual-lab*) and/or directly accessing the real laboratory through a local network or across the Internet (*remote-lab*).

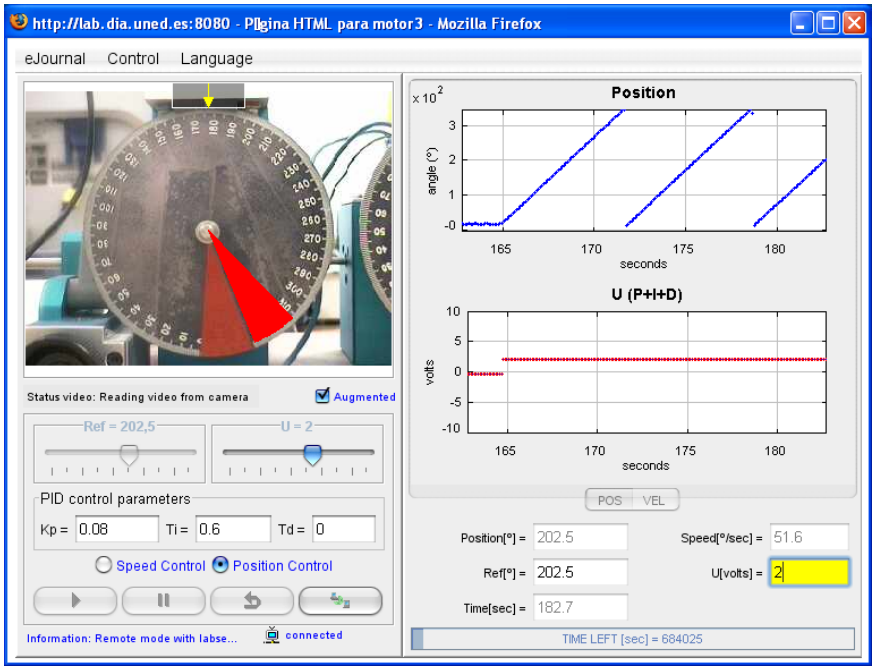
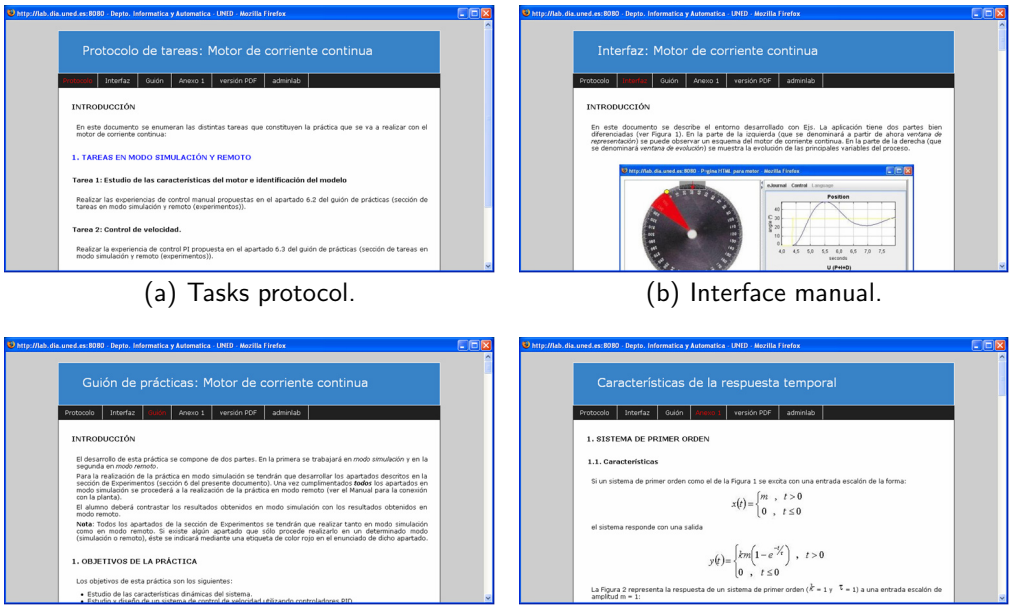


Figure 5.9: The experimentation console of the DC Motor experiment.

Figure 5.9 shows an example of an *experimentation console*. When working in remote mode the *Ejs* applet connects to the real equipment located in the laboratory through *JiL server* such as depicted in Figure 5.7.

Complementary information

Through this module, students have direct access to the theory and practical contents needed to carry out an experimentation session satisfactorily. This information is available in text files in any electronic format (*.pdf or *.doc) or as HTML web pages located anywhere on the Internet. The documentation provided to students must be designed so that it can be followed in an easy and intuitive


Protocolo de tareas: Motor de corriente continua
INTRODUCCIÓN
1. TAREAS EN MODO SIMULACIÓN Y REMOTO
Tarea 1: Estudio de las características del motor e identificación del modelo
Tarea 2: Control de velocidad.
Interfaz: Motor de corriente continua
INTRODUCCIÓN
Guión de prácticas: Motor de corriente continua
INTRODUCCIÓN
1. OBJETIVOS DE LA PRÁCTICA
Características de la respuesta temporal
1. SISTEMA DE PRIMER ORDEN
1.1. Características

(a) Tasks protocol. (b) Interface manual.

(c) Practice guide. (d) Appendix information.

Figure 5.10: HTML Documentation of the DC Motor experiment.

way. This information should be classified according to its role in the completation of these experimental activities. Figure 5.10 shows the documentation in eMersion of the *DC Motor* prototype.

The prototypes developed in the previous chapter have been fully documented. The documents have a homogeneous structure and the content has been written bearing certain practical considerations in mind from a pedagogical point of view. The most relevant aspects to take into account when completing tasks can be summarized as follows:

- ☞ **Activities Protocol**: A first document defines a set of tasks or activities that a student should carry out in order to be evaluated effectively by the teaching staff. This protocol is divided into two parts: *PRE-Labs* activities and *Labs* activities. *PRE-labs* are based on the use of the experimentation console in simulation mode. Thus, the teaching team is ensured that the student has a previous knowledge of the system before working with the real process. On the other hand, *Labs* tasks are based on the use of the experimentation console in remote mode. Remote access to the system is enabled by the teaching staff once the work in simulation mode has been evaluated satisfactorily.

☞ **Practical guide for the experimentation console**: A second document describes each graphical element of the console. Thus, students can use this information as a starter's guide.

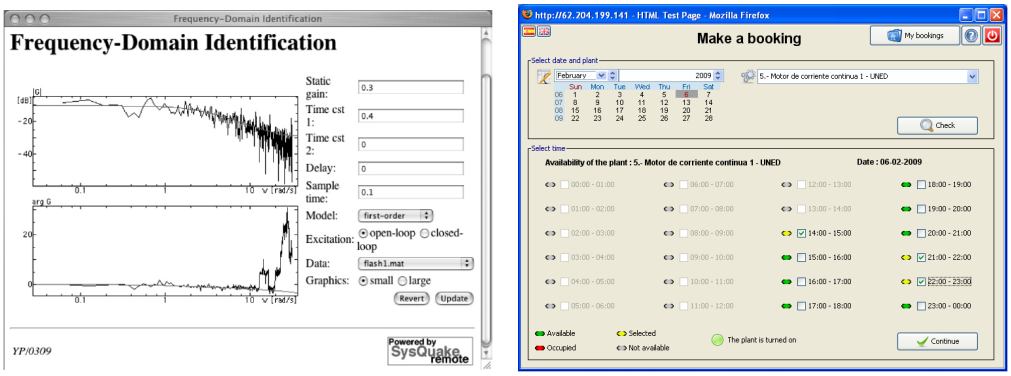
☞ **Modelling and control of the process under study**: A third document provides theoretical and practical information about the process under study such as the mathematical model of the system, the basic theory of control and identification techniques or any additional information.

☞ **Appendices**: It contains any additional information useful for students. For example, general information common to several modules, datasheet of the hardware used, reference tables, etc.

Integration of external web applications

eMersion also offers the possibility of integrating third-party web-based applications to the environment. Thus, the functionality of the system can be increased according to needs. For example, during an on-line experimentation session, students can collect data registers that will be analyzed with specific software tools such as Matlab/Simulink, Scilab, SysQuake, etc. eMersion allows to incorporate *toolkits* to access remotely through their URL. Figure 5.11 shows two examples of this feature.

Figure 5.11(a) shows the external toolkit so-called SysQuake-Remote which was integrated into eMersion at EPFL to sustain interaction during the learning



(a) SysQuake-Remote from EPFL. (b) Bookings System from UNED.

Figure 5.11: Examples of external web applications integrated into eMersion.

process (Gillet et al. 2005). Figure 5.11(b) depicts the *automatic bookings system* developed in this dissertation to manage students' access to the laboratory's real resources. The following chapter describes this external web-based component integrated in the eMersion environment with more details.

Collaboration and interaction module: "The eJournal"

This component plays a key role in the development and deployment of eMersion as a web-based experimentation environment. The *eJournal* is the module that enhances interaction and collaborative work in eMersion. In this workspace, students can save, retrieve, share and even, exchange documents between each other or among workgroups. Figure 5.12 shows the *eJournal* GUI. The objects susceptible to be importable, exportable, or exchangeable in the *eJournal* are called *Fragments*. *Fragments* can be files of any semantic content and students can use them to prepare their session reports.

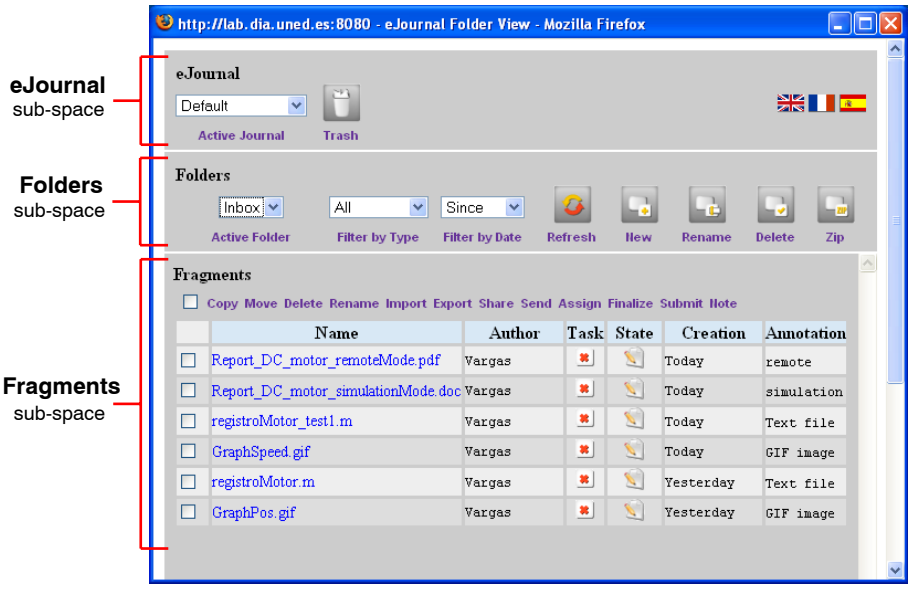


Figure 5.12: The eJournal module of the eMersion environment.

The *eJournal* GUI is composed of three sub-spaces. This division corresponds to the functionality provided by each sub-space. A simplified description of them is provided below:

eJournal Sub-space. It allows students to have access to the *eJournal* space from other groups as long as these groups have granted them access. This

feature fulfills the essential characteristic of web-experimentation environments of *Discretionary Collaboration* seen in Section 5.2.1. Furthermore, a trash icon serves to receive *Fragments* deleted by users. The *Fragments* deleted can be reloaded or definitively deleted. Finally, the internationalization (using the I18N feature of Struts framework) of the application is also included. Languages currently available are *English*, *French*, and *Spanish*.

Folders Sub-space. The Folders sub-space helps organize and deploy *Fragments* inside the *eJournal*. Users can create folders where they put and classify their *Fragments* as they do in the hard disk of a computer. A folder with special features named *Inbox* is automatically created to receive data *Fragments* from other web-components of the experimentation environment. The *Fragments* deployed in the *Fragments* sub-space can be filtered by *type* and *creation date* from two combo-box elements located in this sub-space. A set of icons allows users to create folders, rename and/or delete them and finally, compress the folder selected in the *active folder* selector into a ZIP file.

Fragments Sub-space. The third and last sub-space of the *eJournal* contains a set of useful functions to handle data *Fragments*. Students use the functions *Copy*, *Move*, *Delete*, *Rename*, *Import*, *Export*, *Share*, *Send*, *Assign*, *Finalize*, *Submit* and *Note* to manage fragments and, at the same time, interact and collaborate with other participants of the community of practices (professors, tutors, other students). A list of *Fragments* is deployed as a table in the lower part of this sub-space. Files are deployed in accordance with the *filter* and the *active folder* used at every moment. The columns in the table provide meta information or attributes associated to each *Fragment* as, for example, *Name*, *Author*, *Task*, *Status*, *Creation*, and *Annotation*.

The *eJournal* web-component fulfills a key role in the introduction of the *social learning model* used in this dissertation. Part of the ideas described here can be mapped into actions and situations that occur in a presential laboratory.

5.3 Conclusions

This chapter has provided essential information about how to appropriately face the education of students in a *distributed learning context* through the Internet. For this purpose, the following topics have been discussed:

- The pedagogical aspects to consider when moving from a traditional laboratory context to a flexible learning model across the Internet.
- The major characteristics that a web experimentation environment should fulfill based on the pedagogical aspects previously mentioned.

Additionaly, the solution adopted to implement a *social learning model* for UNED control engineering students has been described. Some of the main conclusions of this implementation can be summarized as follows:

- A complete description of the web-based experimentation environment "eMersion" has been presented.
- Each web-component that composes the environment has been described separately. The reason for that is that, in fact, an eMersion environment is a set of independent web applications which covers all the most relevant aspects of remote experimentation.

Chapter 7 will show the integration of the *e-Learning Layer* and the *Experimentation Layer*. The linking between them will be illustrated by means of a complete remote and virtual control laboratory deployed by eMersion.

6

Access Control to Experimentation Resources

Overview

Sometimes physical resources available in university laboratories do not meet students' demands. In fact, in most cases these have to form workgroups to share the pieces of equipment available in the laboratory. However, in a flexible learning context through the Internet, we need to organize the access to these resources somehow. To overcome this problem, an *automatic booking and authentication system* was developed.

A simple *point to point authentication protocol* to use laboratory resources is first introduced. This current project was thought in such a way that its use can be extended to a network of remote and virtual laboratories. Although this scheme can be applied to remote-labs created using any technology, in this dissertation we have integrated the *point to point authentication protocol* into the JiL server approach explained in Chapter 3.

Finally, a description of the transition towards a booking and authentification flexible scheme inspired in this simple authentication protocol will be provided. The following chapter will describe how the final product (the *automatic bookings system*) has been completely integrated into the eMersion environment.

6.1 Scheduling access to physical resources

6.1.1 Background

In the case of on-line labs that enable web access to real devices (remote workbenches), access time should be booked in advance (Ferreira & Cardoso 2005). The idea is to grant access only to users who meet certain requirements. Users, for example, must be enrolled on the corresponding course and to have been positively evaluated by the teaching staff who is in charge of the course in the simulation stage (a prerequisite to access to physical resources). For this reason, it is necessary to include a module that allows access to authorized users only. These systems can be of two kinds, either *traditional* or *on demand* (Sánchez 2000). The first class is of a similar nature to the one that can be found in conventional laboratory (in a presential context). Timetables are available and each user must access the physical resource needed in the timeslot that the *system administrator* has assigned her/him. In the second class, when a user wishes to access a piece of equipment in the laboratory, s/he must book a free timeslot using web applications provided by this service. Since certain users need more time than others to complete their tasks, the system should be flexible enough. However, a minimum degree of inteligence is required for the system to avoid abuses from users who will book more timeslots than needed and guarantee a minimum number of hours for everyone.

This piece of work will describe a first access protocol to the laboratory's physical resources. For this purpose, a *client application* is authenticated against the *remote server computer* directly connected to the plant and which also contains an authorized users' list kept in a database. Such a list is filled out manually by an *administrator* (usually the teacher or a tutor with these privileges) enabling access to students who fullfil certain requirements.

Finally, once the access protocol has been defined, the inclusion of an automatic mechanism to populate the database was explored. As a result, a full *automatic booking and authentication system* was implemented.

6.2 A simple point-to-point authentication protocol

6.2.1 User authentication

Figure 6.1 depicts the general idea of the p2p authentication scheme implemented. The protocol considers the sending of authorization credentials from the user to the lab-server. The server provides a simple authentication service in which credentials are checked in the local database that contains a list of authorized users. Then, the server returns the result of the authentication attempt to the user and grants or denies access to the plant.

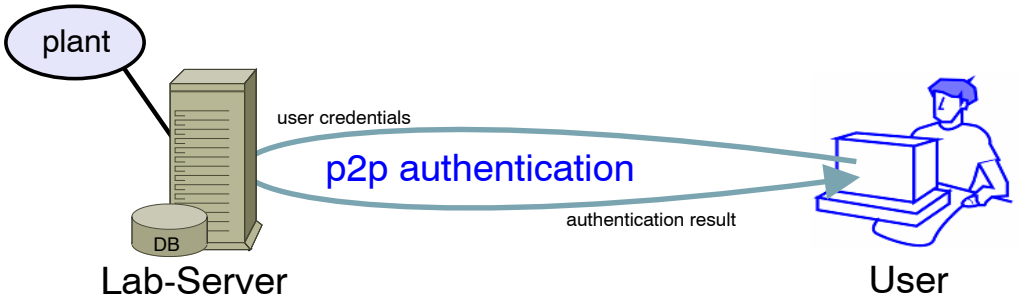


Figure 6.1: Point-to-point authentication protocol between a user and a remote server providing authentication services.

Figure 6.2 illustrates the authentication process. From a client interface point of view, the process suggested consists of a programming module to send a user-name and an encrypted password from the client to the server and obtain an answer from the server indicating the result of the access attempt. The server is therefore responsible for checking whether the username and password exist in the bookings' database and, must also verify whether the user is trying to connect during the timeslot booked.

Although the implementation of the authentication programming modules in the client and server side can be achieved using any type technology, the system was developed using LabVIEW (on the server side) and Java (on the client side) to match the process developed in previous chapters.

As we can see, the authentication process on the server-side generates some

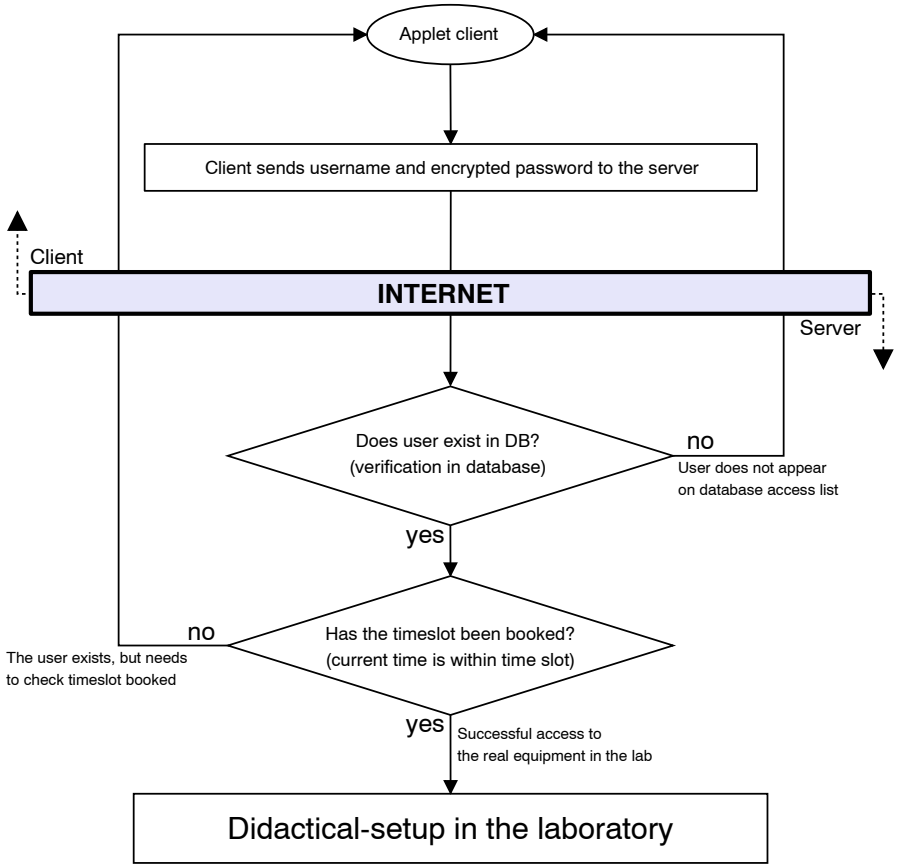


Figure 6.2: Algorithm of the point-to-point authentication protocol.

various issues. The following two sections describe both the structure of the booking database and the LabVIEW program that implements the logic of checking. The integration of this programming module into the *JiL server* will then be described and, finally, the authentication issues on the client side will be addressed using *Ejs*.

6.2.2 A database for the booking of physical resources

A database connected to a real plant located in each server manages user access to physical resources. These databases contain the booking registers for the respective plants. As previously mentioned in Section 6.1.1, databases are initially filled out manually by the administrators of the laboratories. However, Section 6.3 will show an automatic mechanism used to populate them, transforming this simple authentication protocol into a *custom automatic bookings system* for remote experimentation.

A simple database aimed at hosting the bookings was created. The database contains five tables (*accesslist*, *accesslisthistory*, *labstatus*, *labstatushistory* and, *loginresult*). Figure 6.3 shows the structure of the tables in the database.

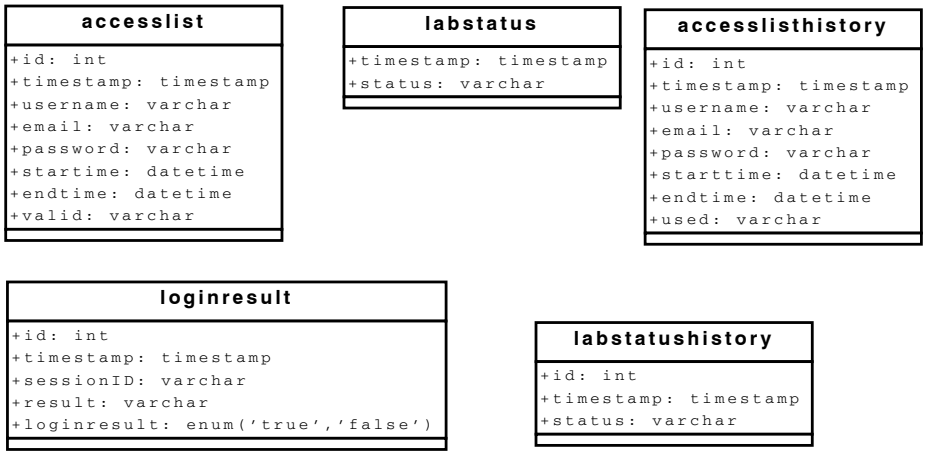


Figure 6.3: Database to host bookings.

The most important table is the *accesslist* because as it hosts bookings. This table acts as a middleware layer between the user connection attempts and physical resources. The other tables can be used to record statistical information about the bookings, the status of the lab (ONLINE, OFFLINE, RUNNING, or UNKNOWN), connection attempts, and, the information about whether a booking has been used or not. Nowadays, only the *accesslist* table is used while the others are reserved for future usage.

id	timestamp	username	email	password	starttime	endtime	valid
1	20090319122105	ohijano	oliver_hijano@hotmail.com	R2FtbXBEcVk=	2008-12-13 15:00:00	2008-12-13 15:59:59	false
2	20090319122129	estudiante	hvargas@bec.uned.es	ZXN0dWRpYW50ZQ==	2008-09-02 15:00:00	2008-09-02 15:59:59	false
3	20090319123224	rvargas	hvargas@bec.uned.es	cmVuYTEzNzY=	2009-04-01 11:00:00	2009-04-01 11:59:00	true
4	20090319122136	ohijano	oliver_hijano@hotmail.com	R2FtbXBEcVk=	2008-12-13 16:00:00	2008-12-13 16:59:59	false
5	20090319122140	ohijano	oliver_hijano@hotmail.com	R2FtbXBEcVk=	2008-12-13 17:00:00	2008-12-13 17:59:59	false
6	20090319122144	ohijano	oliver_hijano@hotmail.com	R2FtbXBEcVk=	2008-12-14 15:00:00	2008-12-14 15:59:59	false

Figure 6.4: Bookings registers in the *accesslist* table of the database.

Each of the registers in the *accesslist* table (see Figure 6.4) corresponds to the bookings of timeslots made locally by a users' administrator (for example, the *teacher assistant* of the course). In the implementation process, we used MySQL server as the database repository. MySQL was chosen as it is a widely extended database management system (DBMS) and, mainly, because free and open-source LabVIEW toolkits can be used to interact with it.

6.2.3 LabVIEW implementation for authentication

In order to offer a wider vision of the LabVIEW implementation for authentication purposes, Figure 6.5 shows the information flow between client and server along the authentication process.

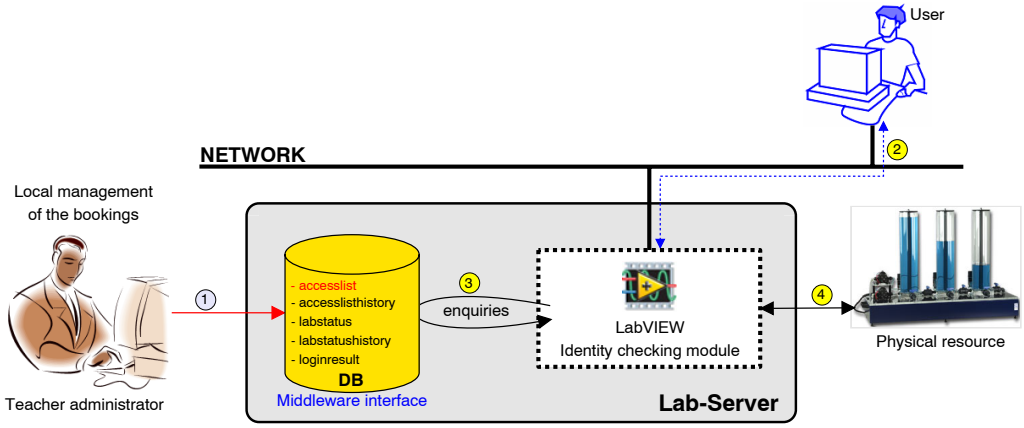


Figure 6.5: Global vision of the first stage of the booking process.

The sequence of actions numbered in Figure 6.5 is briefly described hereafter:

1. An administrator from the lab-server creates a new entry in the database for a student.

2. Once the new entry has been created, the student can attempt to access the remote plant with his/her user credentials (previously sent by the teacher administrator). These credentials are intercepted by a new LabVIEW module named *Identity checking*.

3. The *Identity checking module* verifies user credentials with the data base and reports the result of the access attempt to the client. The client can receive three possible answers:

   - A *message* indicating that credentials do not exist or are wrong.
   - A *message* indicating that credentials are valid but the user is attempting to connect out of the established timeslot.
   - A *message* indicating that credentials and timeslot are fine.

4. If the "ok" message received, the client application can start the data exchange with the real plant located in the laboratory. Otherwise, the client interface will inform the user why access was denied via a warning text message.

The built-in implementation of the LabVIEW *Indentity checking module* can be seen in Figure 6.6. The LabSQL toolkit was used to enquire the database from LabVIEW. LabSQL is a collection of open source VIs developed by Jeffrey Travis Studios (LabSQL 2009) that use the ADO[1] object collection in LabVIEW for users to connect to almost any database, perform SQL queries, manipulate records, etc.

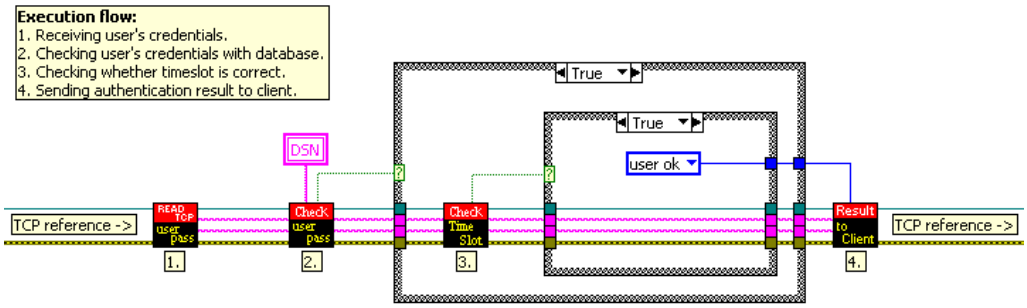


Figure 6.6: LabVIEW *Identity cheking module*. Extract of the block diagram.

Table 6.1 presents a descriptive summary of the internal tasks carried out by each VI of the LabVIEW *Identity checking module*.

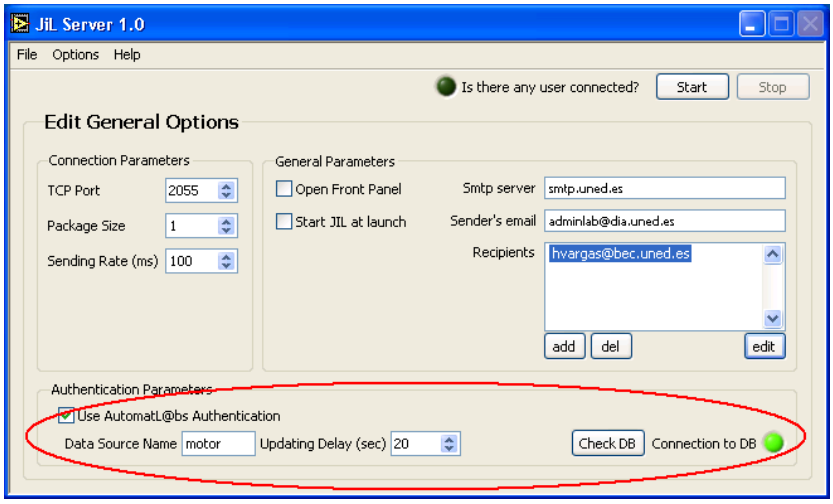
Table 6.1: Description of the main VIs for the *Identity checking module*.

Block	Description
READ TCP user pass	**Read User and Pass** Gets username and password (encrypted in Base64) of the client from the TCP channel.
Check user pass	**Check User and Pass** Queries the database to verify whether username and password are valid. Returns result together with starttime and endtime.
Check Time Slot	**Check Time Slot** If username and password exist, it verifies whether the current time of the server is between the starttime and the endtime of the booking.
Result to Client	**Send Result to Client** Gets the authentication result message from the previous block and sends it to the client application through the TCP channel.

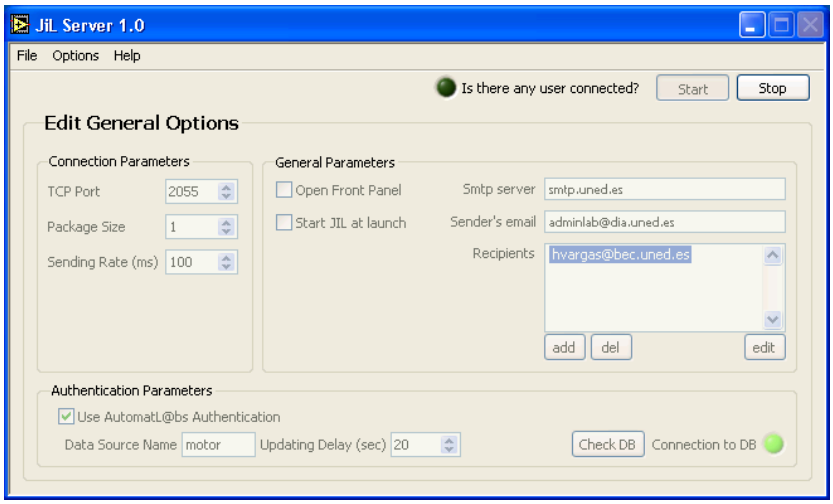
[1]Microsoft's ActiveX Data Objects (ADO) for accessing data sources.

6.2.3.1 Integration into the JiL server

The LabVIEW module previously described has been integrated into the JiL server as a new command for client to use. By adding this new feature, the JiL server application explained in Chapter 3 looks as shown in Figures 6.7 and 6.8.



(a) Edit General Options window.



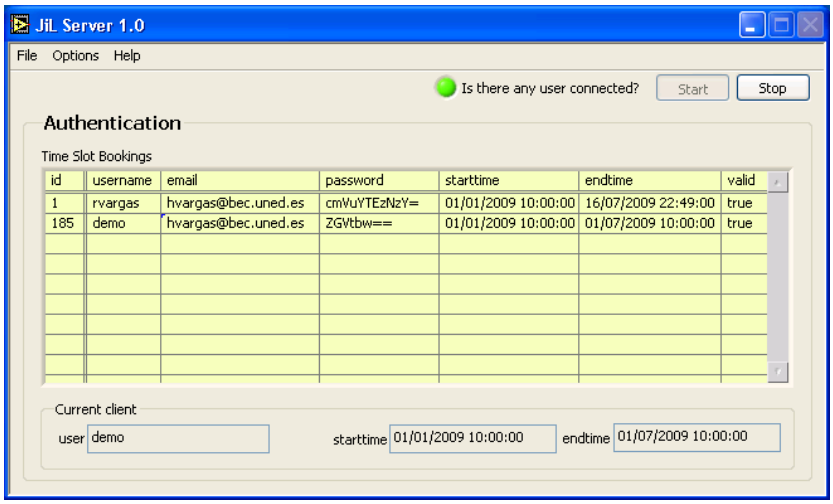
(b) Edit General Options disabled when started.

Figure 6.7: Setting up options in JiL server.

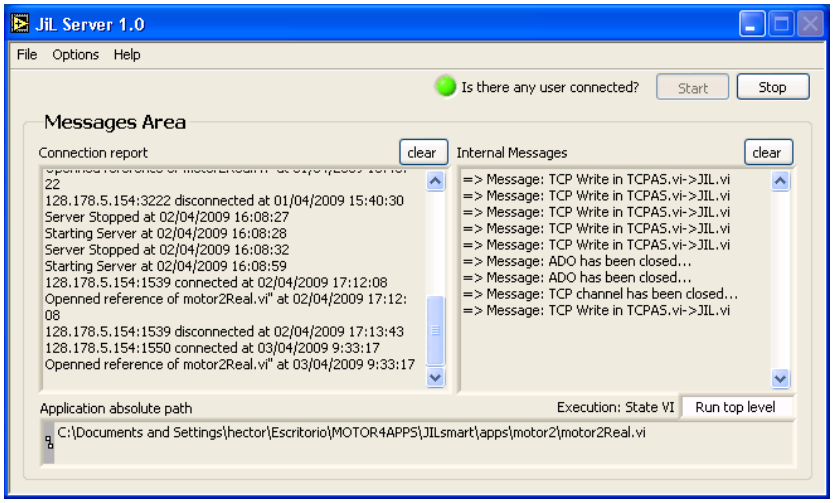
The Edit General Options window was modified to configure authentication parameters in the JiL server. Figure 6.7(a) shows the new settings added to this configuration zone (highligthed with a red elipse). Once the database management system (MySQL) has been installed and the tables created, a new data source should be created through an ADO connection. With this setting, the JiL server is able to connect to the database. A user only needs to provide the DSN

reference (*Data Source Name*) and check the connection to the database pushing the *Check DB* button. If the connection is successful, an indicator led labelled *Connection to DB* is turned on. When the server is started, all the configuration options are disabled (see Figure 6.7(b)).

Other two visualization windows (*Authentication* and *Output Messages* areas) can pop up from the *Options* menu. The table *Time Slot Bookings* in Figure 6.8(a) shows the new incoming bookings; the lower part of this window shows which user is connected. Finally, Figure 6.8(b) shows a tracking report of connections, disconnections, internal messages of the server and, the absolute path of the VI target.



(a) Bookings visualization.


JiL Server 1.0
File Options Help
Is there any user connected?
Start
Stop
Messages Area
Connection report
clear
Internal Messages
clear
128.178.5.154:3222 disconnected at 01/04/2009 15:40:30
Server Stopped at 02/04/2009 16:08:27
Starting Server at 02/04/2009 16:08:28
Server Stopped at 02/04/2009 16:08:32
Starting Server at 02/04/2009 16:08:59
128.178.5.154:1539 connected at 02/04/2009 17:12:08
Openned reference of motor2Real.vi" at 02/04/2009 17:12:08
128.178.5.154:1539 disconnected at 02/04/2009 17:13:43
128.178.5.154:1550 connected at 03/04/2009 9:33:17
Openned reference of motor2Real.vi" at 03/04/2009 9:33:17
=> Message: TCP Write in TCPAS.vi->JIL.vi
=> Message: TCP Write in TCPAS.vi->JIL.vi
=> Message: TCP Write in TCPAS.vi->JIL.vi
=> Message: TCP Write in TCPAS.vi->JIL.vi
=> Message: TCP Write in TCPAS.vi->JIL.vi
=> Message: ADO has been closed...
=> Message: ADO has been closed...
=> Message: TCP channel has been closed...
=> Message: TCP Write in TCPAS.vi->JIL.vi
Application absolute path
Execution: State VI
Run top level
C:\Documents and Settings\hector\Escritorio\MOTOR4APPS\JILsmart\apps\motor2\motor2Real.vi

(b) Status tracking (logging).

Figure 6.8: JiL server with authentication. Setting up and status visualization.

6.2.4 User authentication issues in *Ejs*

On the client side, the introduction of the authentication module in the *Easy Java Simulations* interfaces meant following two steps:

1. To define a custom method that uses any encriptation mechanism in order to provide a first security level when the password is sent across the Internet. In this case, we used the encriptation algorithm known as *base64*[2] to match the eMersion platform. Listing 6.1 shows how this algorithm is coded. The non-encrypted password is given so as to get the encrypted version.

Listing 6.1: Java method to encrypt a string in Base64.

```
1 public static String encBase64 (String passNoEncrypted) {
2
3   Base64Encoder encoder = new Base64Encoder(passNoEncrypted);
4   String passEncripted = encoder.processString();
5
6   return passEncrypted;
7 }
```

2. To use the new Java method `public int authenticate(username, passEncrypted)` of the class *Jil.class* in the *jil.jar* library introduced in Section 3.3.4. When this method is invoked from a client, the Java application reports the user's credentials to the server side, that is, the username and the password previously encrypted as seen in Listing 6.1. The method returns an integer value indicating the connection attempting result. If the value is 1, this means the username and password do not match with any register in the database. If the result is 2, then this implies the username and password are recorded in the database but the user is attempting to connect outside the timeslot. And finally, if the result is 3, user's credentials and timeslot are valid and the user is granted access to the remote plant.

The above logic should be programmed in the client side Java application in order to provide this authentication service to the graphical user interface.

[2]The term Base64 refers to a specific MIME content transfer encoding. It is also used as a generic term for any similar encoding scheme that encodes binary data by treating it numerically and translating it into a base 64 representation.

6.3 A flexible scheme for booking and authentication

Previous sections described the authentication process that occurs when a booking is carried out locally by the administrator in the database. Now, the extension of this approach toward a flexible scheme is presented. Based on Figure 6.5, the teacher administrator has been replaced with an automatic bookings modality. Figure 6.9 depicts the new scenario.

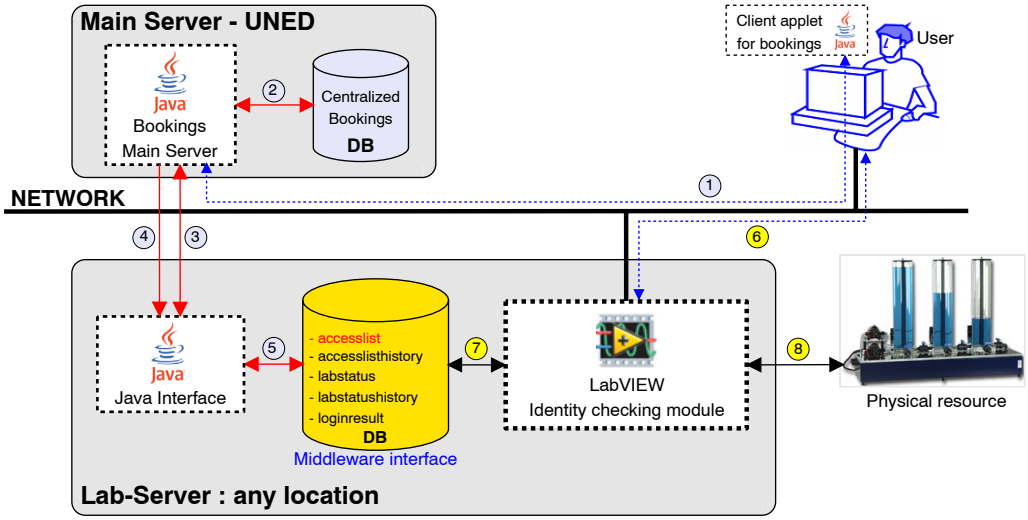


Figure 6.9: A flexible scheme for bookings and authentication process.

This scheme enables students to book themselves. The basic idea consists of filling out the reservations database automatically from the client side by means of a web interface. The full system is composed of three new applications which all provide this functionality. In the case of the first application, a Java applet was developed to perform new bookings on the client-side (see *Client applet for booking* in Figure 6.9). With regards to the second application, a centralized server application also developed in Java manages reservations, synchronism, and communications between the client applet for bookings and the *Lab-Server* (see *Bookings Main Server* in Figure 6.9). Finally, an additional Java module located in the *Lab-Server* was developed (see *Java Interface* in Figure 6.9). This module informs the *Bookings Main Server* of the current state of the *Lab-Server* and other parameters that the central server needs. For example, a new reservation will be effectivelly made when the *Lab-Server* is turned-on and working perfectly.

On the other hand, information about the *time zone* of the *Lab-Server* in relation to the GMT[3] is also reported by this module to the central-side. This information is paramount when a *Lab-Server* is located outside the *Main Server time zone*. Thus, when a new booking for a *Lab-Server* is made, the central side server accounts for the *time zone* of the *Lab-Server* (reported by the *Java Interface*) to calculate the temporal lag between both and insert the correct timeslot in the database.

Summarizing, the full process is divided into two stages in order to use a physical resource of the laboratory and is described as follows:

Booking Stage: Figure 6.10 shows a state diagram of the booking process.

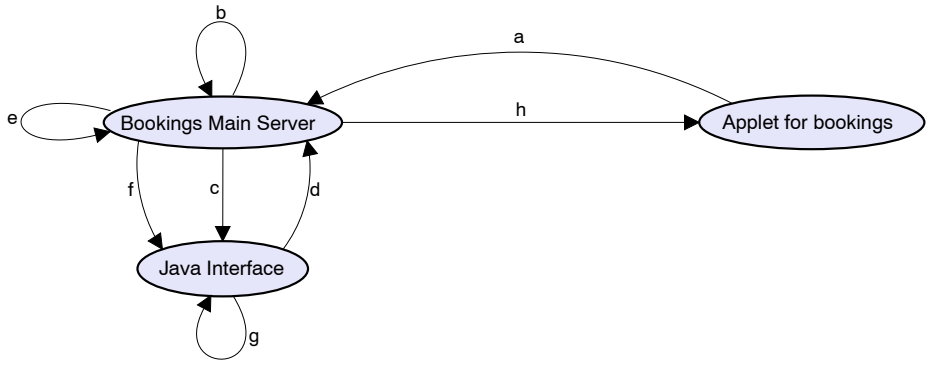


Figure 6.10: State diagram of the booking process.

A description of the state flow during a *reservation* is as follows:

a. The *Applet for bookings* requests a new reservation (step 1 in Figure 6.9).

b. The *Bookings Main Server* takes the request and saves it in a local DB (step 2 in Figure 6.9).

c. The *Bookings Main Server* requests the *Java Interface* for its *time zone* (step 3 in Figure 6.9).

d. The *Java Interface* provides its *time zone* to the *Bookings Main Server* (step 3 in Figure 6.9).

[3]Greenwich Mean Time (GMT) is the world wide reference time to calculate *countries' time zone* around the world.

e. The *Bookings Main Server* calculates the time lag and amends the timeslot.

f. The *Bookings Main Server* reports the new register to the *Java Interface* (see step 4 in Figure 6.9).

g. The *Java Interface* receives the register and inserts it in the *Lab-Server* DB (step 5 in Figure 6.9).

h. The *Bookings Main Server* tells the client that the new reservation has been done (see number 1 in Figure 6.9).

Authentication Stage: A state diagram of the authentication process is depicted in Figure 6.11.

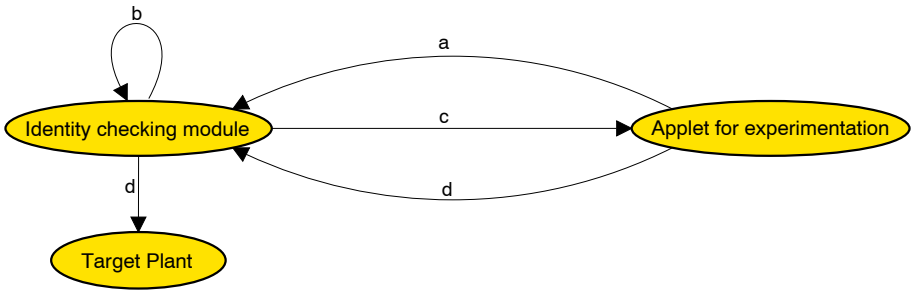


Figure 6.11: State diagram of the authentication process.

A detailed description of the state flow during *authentication* is as follows:

a. The *Applet for experimentation* starts the process by sending user credentials (see step 6 in Figure 6.9).

b. The *Identity Checking Module* receives the keys and checks whether user exists in local DB. Should this be the case, it then checks whether the connection attempt is between the starttime and the endtime of the timeslot reserved (see step 7 in Figure 6.9).

c. The *Identity Checking Module* sends the result of the checking to the *Applet for experimentation* (see step 6 in Figure 6.9).

d. If the checking result is ok, then the *Applet for experimentation* gets free access to the *Target Plant* (see step 6 and 8 in Figure 6.9).

➠ **Note**: The *bookings and authentication system architecture* presents three interesting advantages from a maintenance point of view. It provides a backup of all bookings hosted in a centralized database. Thus, in the case that a *Lab-Server* with valid bookings is damaged, these could be retrieved later by the *Lab-Server* from the *Central Server*. The authentication process being carried out directly with the *Lab-Server* represents a second advantage. And thirdly, the administrators of a *Lab-Server* can manage the bookings locally. In case of problems with the central-side, bookings can be made manually.

6.3.1 The automatic bookings system client interface

So far, the global architecture of the *automatic bookings and authentication system* has been described. The detailed steps to follow in order to make a reservation are now presented. Figure 6.12 shows the user interface of the *Applet for bookings* whereby students perform their reservations in any experimentation laboratory.

First of all, the process to make a booking implies the student requests a reservation, and secondly that, the response of the bookings system indicates date and time assigned to use for the remote plant. Steps to follow to book are described in detail below:

1. Student should be identified by a login and password registered in the database (Figure 6.12(a)). User name and password to access the remote system are sent to the student by e-mail once the simulation stage has been accepted by the tutor.

2. When user has accessed the bookings system, s/he must choose a time and date as well as the remote laboratory (Figure 6.12(b)).

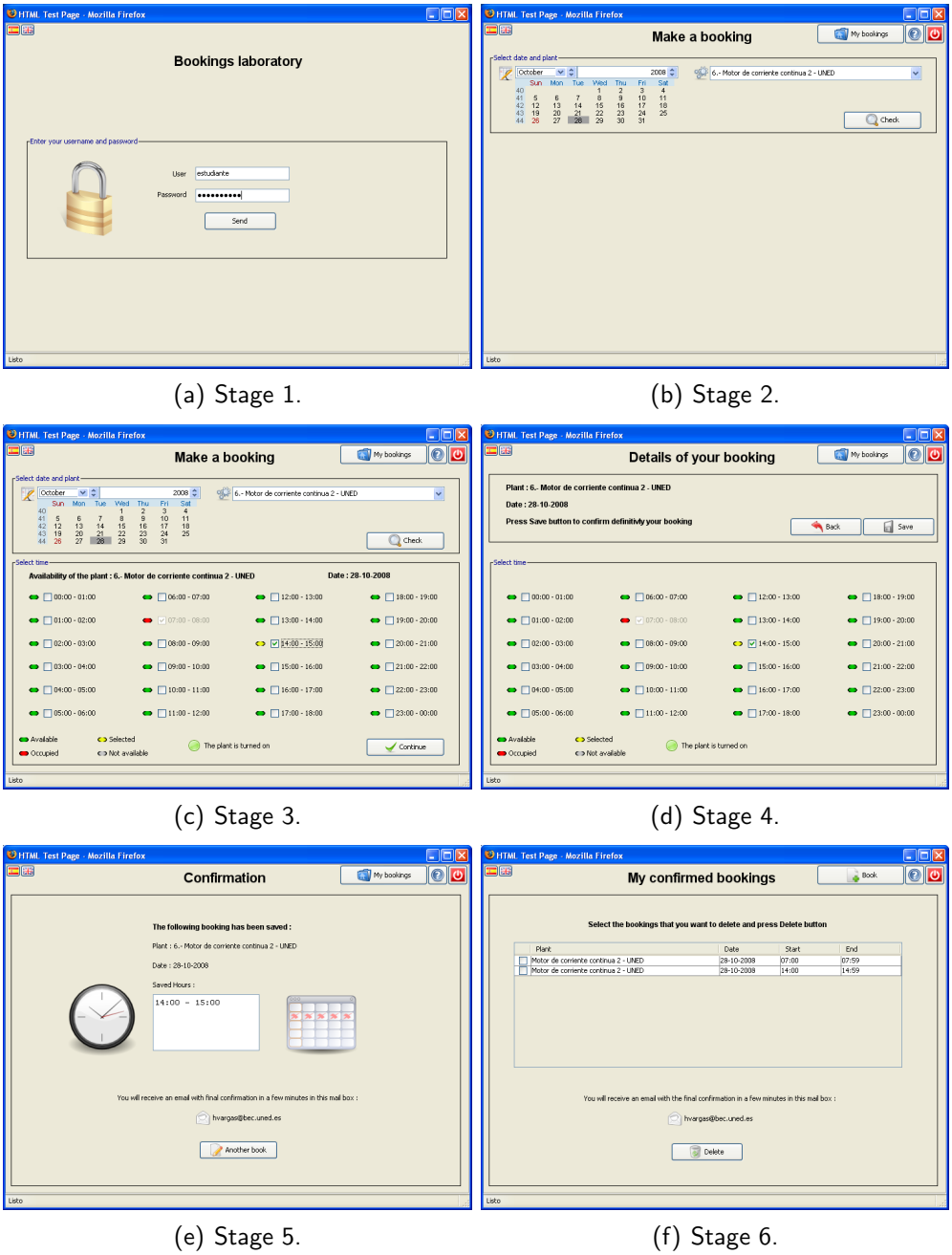
3. Afterwards, the student must check if the remote plant selected is available on the chosen day (Figure 6.12(c)).

4. The student must select the timetable established to use the remote-lab (Figure 6.12(d)). At present, students are allowed up to 6 hours per experiment with the constraints of 2 hours within the same day, with a maximum

of 4 hours per week.

5. The booking system confirms the reservation. The user also receives a confirmation email (Figure 6.12(e)).

6. Finally, the system shows a bookings list with the registered user (Figure 6.12(f)). Reservations can be removed from the list up to 24 hours before.



(a) Stage 1. (b) Stage 2.

(c) Stage 3. (d) Stage 4.

(e) Stage 5. (f) Stage 6.

Figure 6.12: Interfaces involved in the reservation process.

6.3.2 The automatic bookings system server

An administrator for the booking system is in charge of the server configuration. Figure 6.13 shows the graphical user interface of the *Bookings Main Server* whereby the administrator can configure the system's main parameters. This server, located at the Department of Computer Science and Automatic Control of the UNED, is responsible for storing all the reservations made in the system. This way, this computer must be connected, via the Internet, to every *Lab-Server* available. So, any *Lab-Server* connected to the Internet could benefit from this bookings service.

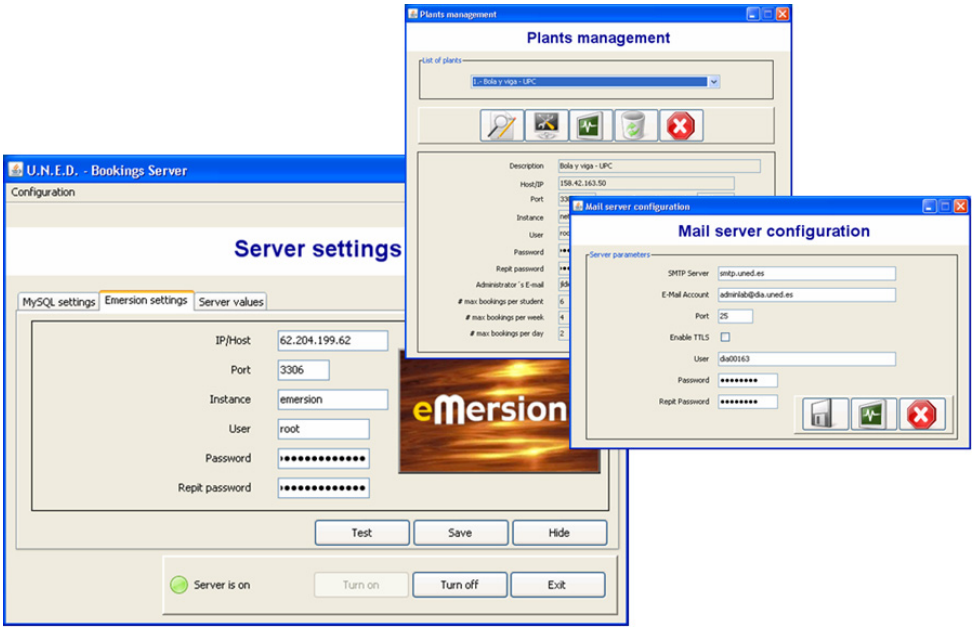


Figure 6.13: Server site of the automatic bookings system.

The most important configuration parameters of the server are the following:

1. Configuration of the supervisor's e-mail account of each laboratory. The system confirms reservations made by users sending an e-mail to the supervisor. Also, if the *Lab-Server* is switched off when a new reservation is made, an e-mail is sent to the *Lab-Server administrator* reporting operation went badly.

2. IP address of the server computers connected to the laboratory plants (*Lab-Servers*) which are suscribed to the bookings system.

3. IP address and port of the MySQL database from eMersion. This information is necessary since the *Bookings Main Server* allows access to the system to users on the eMersion list only.

4. General parameters of the server as, for example, the communication port with the *Java Interface* of every *Lab-Server*, updating frequency of the plants (database in *Lab-Servers*), destination of the log files, etc.

5. Schedule constraints for each one of the practical experiments.

6.4 Conclusions

This chapter has described the implementation of the *Automatic Bookings and Authentication System* that manages access to and use of the physical resources of the remote laboratory. This development allows for a rational use of resources, an essential issue to address in most universities where the number of didactical-setups to attend the students demand is insufficient.

The global architecture of the system has been thought in such a way that any *Lab-Server* (from different locations) can use this service. Chapter 8 will present two pilot experiences carried out with the on-line experimentation system developed in this dissertation. Both use the *automatic bookings system*. The first one uses it with the physical systems located in the Department of Computer Science and Automatic Control of the UNED and the second one, uses the resources of different universities around Spain.

This dissertation considers the *automatic booking and authentication system* as part of the *e-Learning Layer*. This is because the following chapter will show how the bookings system was completely integrated into eMersion as an *External Toolkit* that belongs to the own experimentation environment.

7
Integration of Layers

Overview

In this chapter the integration of the *Experimentation and e-Learning Layers* is addressed. Low-level linkages among different pieces are required to ensure the appropriate functioning of the full environment.

The eMersion environment plays a key role in this part of the dissertation, since, this application could be considered as a wrapper of the other components. The integration of *Ejs applications* into eMersion is first introduced. Then, the inclusion of the *automatic bookings and authentication system* as a new external application in the environment is shown.

Finally, the last section shows the integration of the virtual and remote control laboratory of the *three-tank system* (described in Chapter 4) into eMersion. A summary of the most important steps to follow to obtain the final result is provided.

7.1 Linking layers

So far, the *experimentation and e-learning layers* have been presented separately to maintain a certain order before reaching the final result. Thus, this chapter is intended to describe the final linkage between both layers in order to get the system working as a whole.

As mentioned in previous chapters, web-based experimentation for educational purposes should provide the opportunity for students to generate on-the-fly data registers of their experiments in both simulation and remote mode for post analysis. In the particular case of this work, these data fragments are stored in the *eJournal* workspace. Since the output of a component of the *experimentation layer*, as the *Ejs console*, is going to be the input for a component of the *e-learning layer*, such as the *eJournal*, the linkage between both should be solved. About this subject, two things have been addressed in this disseration:

1. The definition of the type of *data fragments* generated from the *experimentation console* (*Ejs* applications).

2. The integration of *Ejs* applications into eMersion to save *data fragments* to the *eJournal* space.

On the other hand, the web experimentation environment requires to integrate some supplementary components to give access to other pieces of information requested during the learning process.

eMersion automatically makes the linkage between the web-components above mentioned. This task is carried out during the creation of a *working-module* in eMersion. A *module* is, in a few words, the final web interface (eMersion's facade or cockpit) where students work and therefore, from where they should have access to any further web-component. From an eMersion management point of view, the creation of a module is just a part of the configuration process, however, it is precisely there that the integration of every web-component is carried out. A complete summary of both the eMersion management and the cockpit usage can be found in (Esquembre et al. 2007) and Appendix C, respectively.

7.2 Integration of *Ejs* applications in eMersion

Reports about the students' work made during a remote experimentation session are required by the teaching staff. These results are based on the data registers obtained when performing the practical experiments with the help of the experimentation console. This section is devoted to explaining how and what type of data registers can be obtained from the *Ejs applications*.

7.2.1 *Ejs* built-in methods to save data in eJournal

Client-side Java applications can easily be integrated into eMersion with the help of predefined built-in methods of *Ejs* (Esquembre et al. 2007). These methods were used in this dissertation to save data fragments in the *eJournal* space. Methods used and their functionalities are described below:

```
public boolean _saveImage(String fileName, String compName);
```

Saves the image of an element *compName* of the view to the file *fileName*.

```
public boolean _saveText(String fileName, String textData);
```

Saves the text *textData* to the file *fileName*.

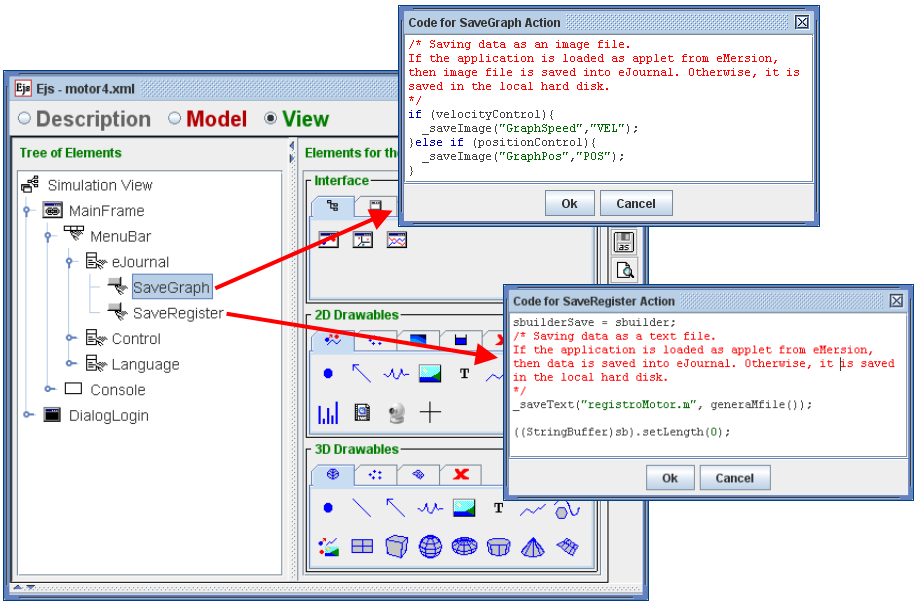


Figure 7.1: *Ejs* built-in methods to link the applet to the *eJournal* workspace.

Figure 7.1 shows the use of these methods in the *DC motor* prototype. They are invoked via the *action* property of buttons *SaveGraph* and *SaveRegister*. When these methods are invoked, they are internally launched in an independent Java thread in order not to interrupt the normal execution of the main loop of the *Ejs* application.

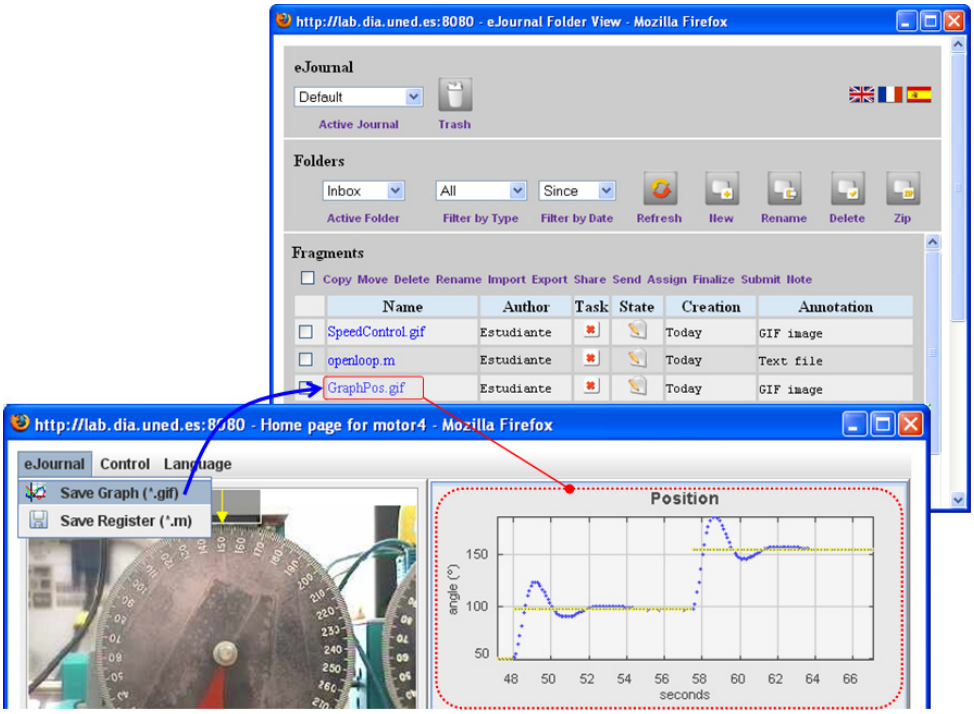


Figure 7.2: Saving data from the *Ejs* console to the *eJournal* space.

Figure 7.2 shows where the buttons are located. Here, it is important to notice that *Ejs* methods internally check whether the Java application is loaded as an applet. If this latter condition is satisfied, then *data fragments* will be saved in the *eJournal* database and will remain available for a later analysis. Otherwise, the *fragment* is saved in the local hard disk of the client computer.

7.2.2 Defining types of data fragments

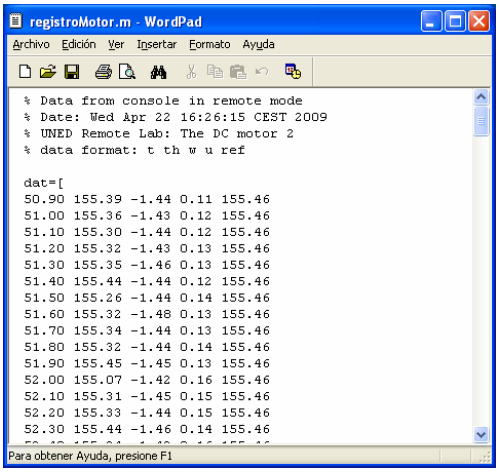
The virtual and remote control applications developed in this dissertation can save data in two formats as mentioned in the previous section:

1. Generic text data files (*.txt) with the values of some variables.

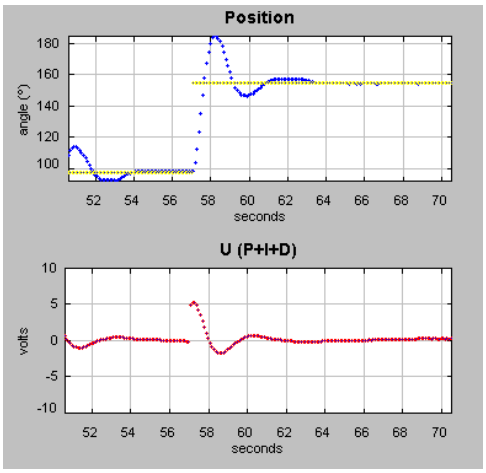
2. Image files displaying the scope area of *Ejs applications* (*.gif).

The temporal piecewise of data to save is what exists in the internal data buffer of the application at the moment of invoking the corresponding method. Circular buffers were used to keep the most recent data ready to be saved. When data are saved in text format, arrays from these circular buffers are turned into strings to use the `_saveText` method. Once the data has been converted to string, the Java API to manipulate *strings* is used in order to structure its presentation.

Figure 7.3 displays two examples of *data fragments* saved from an *Ejs console*. Figure 7.3(a) shows an example of a generic text file and Figure 7.3(b) shows the image of a signal scope of an *Ejs* view saved as an *image file*.



(a) Generic text data file (*.m).



(b) Image data file (*.gif).

Figure 7.3: Types of data fragments in the *eJournal* space.

Special care was given to ensure the text data file has a Matlab-compatible structure. This means students can load and analyze the data in the Matlab workspace without extra manipulation. Furthermore, a header as comment has been added at the top of the file. This header provides information about whether the data was saved in simulation or remote mode, the date when this was done, the remote equipment used, and what the name and order of the variables are.

7.3 Linking all: Work modules in eMersion

As mentioned in Section 7.1, the management of *work-modules* in eMersion is closely related to the linkage of all web-components of the environment. A *mod-*

ule is part of a *course* in eMersion and a *course* can contain several work-modules which somehow represent the different types of practices or "laboratories" available in the system. When managing a course, the administrator can create as many modules as s/he needs. To create a new module, the teacher administrator of the course must fill out a web-form (see Figure 7.4).

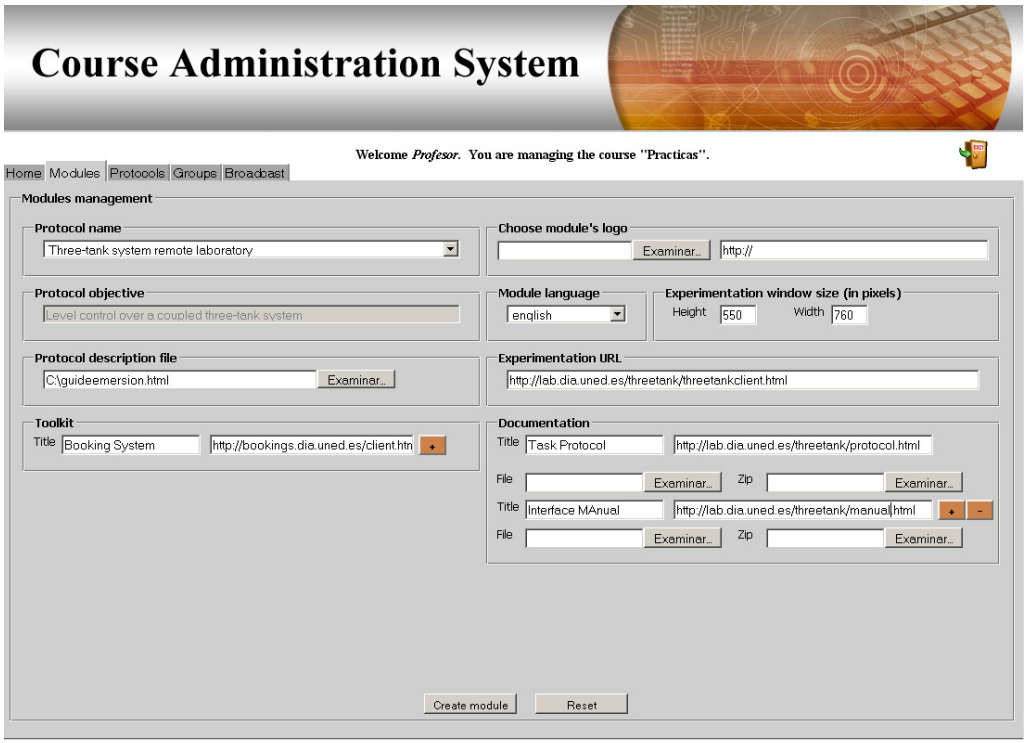


Figure 7.4: Creating a new module (included into a course) in eMersion.

As seen in Figure 7.4, most of the setting parameters needed to create a new module are related to the URL of each web-component that integrate the module. A brief description of the contents of the web-form in Figure 7.4 is given below:

- **Protocol name**: The name of the tasks protocol created previously to the current *module* setting.
- **Protocol objective**: A short description about the objectives of the *module*. This description will appear on the *navigation bar* of eMersion.
- **Protocol description file**: An HTML or PDF file containing an eMersion's guide. This is the first document to be consulted by users.
- **Toolkit**: Integration of external web-applications. A course's administrator

can provide as many URLs as external toolkits s/he wishes. For example, to integrate the *Automatic Bookings System*, the URL of the client interface of the bookings application must be included (see Figure 7.4).

- **Choosing the module's logo**: A custom logo can be used for the *module*. The image file could be located in the local hard disk or any URL on the Internet. If no logo is provided, the eMersion logo is used by default.
- **A language module**: The course Administrator can choose between three different languages: English, French, or Spanish.
- **Experimentation window size (pixels)**: The size in pixels of the pop-up window containing the experimentation console (*Ejs* applet).
- **Experimentation URL**: The URL where the experimentation console is reachable on the Internet. Servers hosting the applets are not restricted to a specific location.
- **Documentation**: The link to the theory and any other document should be indicated here. The field *Title* provides a representative name of the subject of the documents. The content of the document is indicated by means of its URL.

eMersion uses all this metadata information to create a module. A module is composed of a set of JSP, HTML pages (based on the metadata information) automatically created for the eMersion's course management system. When a final user has access to the experimentation environment to carry out an experimental session, s/he is really accessing the web application that constitutes a working module. Hence, it is possible to say that a module represents the final facade of the web-based experimentation environment.

An administrator course can create as many *working modules* as virtual and remote control laboratories s/he has to develop. For the purpose of this dissertation three *modules* were created, which correspond to the three remote laboratory prototypes presented in Chapter 4. For each of them, all the neccesary documentation was developed following recommendations described in Chapter 5.

The automatic bookings system client interface is easily integrated into a *working module* just by providing its URL.

The following section will show the module of the *three-tank prototype* fully integrated into eMersion. The interoperability of all web-components described along this dissertation is shown hereafter.

7.4 A remote laboratory integrated into eMersion

Figure 7.5 shows a complete view of the experimentation environment eMersion during a practical session with the *three-tank system* in remote mode. As mentioned in Section 5.2.4 the environment is composed of five independent web-applications: *navigation bar*, *eJournal*, *experimentation console*, *on-line information*, and *external applications*.

The *navigation bar* gives access to the other environment's web resources. From the link "Access Protocol", users can obtain a complete user's guide of the environment.

The *eJournal* resource provides a shared workspace for users to communicate and collaborate during the learning process. The *eJournal* allows students to save, retrieve, and interchange their experimental results and documents. Furthermore, the presentation of results and discussing with teaching staff can be done using the options provided for these purposes. They can also organize the information collected during experimental sessions as well as an on-line repository works. Work tracking and awareness could be implemented based on this information.

A collection of *HTML pages* accessible from the same environment permits students to visualize all the documentation about the practical exercise. Moreover, each web page includes a PDF document which contains the same information than the web page. This option can be used by students to download the experiments as electronic files.

The applications developed with *Ejs* can be easily integrated into the eMersion environment since they are prepared to interchange data with the *eJournal*

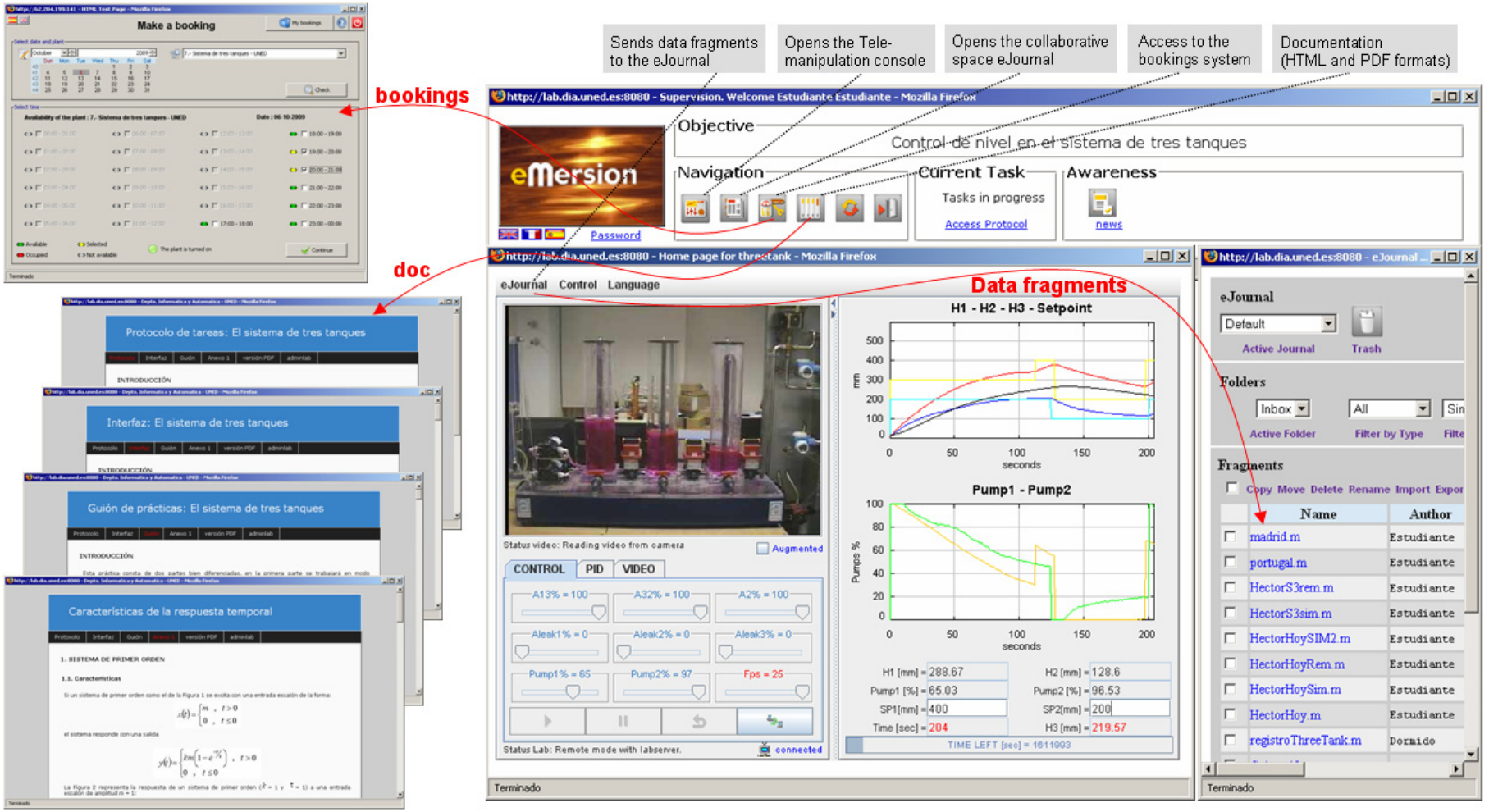


Figure 7.5: eMersion's facade. Remote session using the three-tank system.

space (Figure 7.5, *eJournal* option). Thus, students can use the results obtained (images of the system's evolution or data registers) in the experimentation sessions to ellaborate their reports for the final assessment.

The user interface of the *booking system* has been completely integrated into eMersion. This means, the students can make their reservations from the experimentation environment in order to complete remote experiments.

7.5 Conclusions

The linkage and interoperability of all the pieces of the remote experimentation system of this dissertation has been shown. This mixture of web-components working at the same time both synchronously and asynchronously was the big challenge to reach during the development of this thesis.

The software tools (*Ejs*, LabVIEW, and eMersion) used provide considerable benefits compared to other alternatives. Also, and thanks to this work, the connection between these three software tools have correctly been implemented and tested. *Ejs* applications can be integrated into eMersion in a simple and straightforward way through specific built-in methods. The eMersion management system is what allows the linkage between the web-components that constitute a remote laboratory.

Finally, the next chapter presents some results obtained from testing the system. Two pilot experiences were carried out to test the system and check the students' perception regarding the use of the environment.

Part III

ASSESSMENT

8

System Assessment

Overview

Capturing the students' perception of their learning experiences is a key issue to evaluate the quality and value of the experimentation environment as a teaching tool. Two real experiences were carried out to test the remote experimentation system developed in this dissertation: The *UNED pilot experience* and the *AutomatL@bs project*.

During the UNED pilot experience, students from this institution were encouraged to use the new web-based remote experimentation system to perform their practical activities. Some preliminary results of this experience were extracted and analyzed in this chapter.

In the AutomatL@bs project a more exhaustive test of the system was performed. The experience consisted in integrating virtual and remote control labs from other Spanish universities to produce the first Spanish network of web-based control labs. This study was designed to increase the quality and robustness of the network of virtual and remote laboratories aimed at a higher number of students and teachers with different teaching and learning concerns. In this sense, a set of graphics will show the main results of this evaluation.

8.1 A first experience from the UNED

In order to evaluate the first version of the experimentation system, a pilot experience was carried out during the academic year 2006-2007. Figure 8.1 shows the website which students used to access the remote experimentation system.

Laboratorio Remoto. DIA - UNED - Mozilla Firefox
Archivo Editar Ver Historial Marcadores Herramientas Ayuda
http://lab.dia.uned.es/rlab/
uned
Departamento de Informática y Automática
PRINCIPAL DIA UNED
adminlab
Laboratorios virtuales y remotos
Sistema 1
Sistema 2
Sistema 3
Heatflow
Tres Tanques
Motor
Laboratorio
Departamento de Informática y Automática
Información
Presentación
Laboratorio Virtual
Laboratorio Remoto
Sistemas disponibles
Agradecimientos
Conexión
Requerimientos
Acceso
Enlaces
Easy Java Simulations
Recursos en la red
Información > Presentación
Presentación
Bienvenido al laboratorio virtual y remoto del Departamento de Informática y Automática de la UNED. Estas páginas contienen la información preliminar necesaria para que el estudiante que está matriculado en la asignatura de Automática I de la especialidad de Física Industrial en la carrera de Ciencias Físicas de la UNED pueda acceder a nuestro entorno de simulación y experimentación a distancia para realizar el conjunto de prácticas de laboratorio que son necesarias para poder superar la asignatura.
Listo

Figure 8.1: UNED pilot experience home page.

Students worked on the three prototypes of virtual and remote laboratories located at the Department of Computer Science and Automatic Control: the *three-tank system* (liquid level control), the *heat-flow system* (temperature control), and the *DC motor* (speed and position control).

The evaluation was completed during the summer term of 2007 with 50 students enrolled in the Physics degree program at the UNED (for which the process control laboratory is a compulsory subject). The evaluation questionnaires returned at the end of the term showed the opinions of the audience, who rated the different statements of the survey as strongly agree, agree, neutral, disagree, or strongly disagree. These answers are summarized in Table 8.1.

The analysis of the evaluation results showed that the pilot experience was a very promising achievement. The experience also helped to extract some information about the positive and negative aspects of a remote experimentation system for teaching in the field of engineering (Dormido et al. 2008).

Table 8.1: Student questionnary results (2006-2007), UNED.

Sub-scale	%SA	%A	%N	%D	%SD	%NA
Learning value	55.5	33.3	11.2	0	0	0
Value added	2.5	2.5	1.5	0	0	0
Design and usability	38.8	55.5	5.7	0	0	0
Technology function	53.3	13.3	13.3	0	0	20.1

SA: Strongly Agree. **D**: Disagree. **A**: Agree.
SD: Strongly Disagree. **N**: Neutral. **N/A**: None of the previous.

One should highlight that the UNED is an important distance learning institution in the world. Experiments should be carried out once and again improved and encouraged. These should be seriously taken into consideration so as to prepare programs adapted to the *European Space of Higher Education*.

8.2 The AutomatL@bs project

The second pilot experience consisted of expanding the first study to a national scope (academic year 2007-2008) to carry out a more exhaustive test of the experimentation system (see Figure 8.2).

The workgroups of the control engineering research area taking part in the **AutomatL@bs** initiative were the National University for Distance Education (UNED), the University of Almería (UAL), the University of Alicante (UA), the Polytechnic University of Valencia (UPV), the Polytechnic University of Catalonia (UPC), Miguel Hernández University (UMH), and the University of León (UNILEON).

The main challenge of this experience was the integration of the hardware, software, and human resources of the project participants into the web-based experimentation environment hosted by the Department of Computer Science and Automatic Control of the UNED (AutomatL@bs 2009, Vargas et al. 2009b, 2010).

The various groups committed to the following:

1. To provide a physical system hosted by the participants to the AutomatL@bs network. This piece of equipment should be for the exclusive use of the network during the months when the laboratory is open to students.

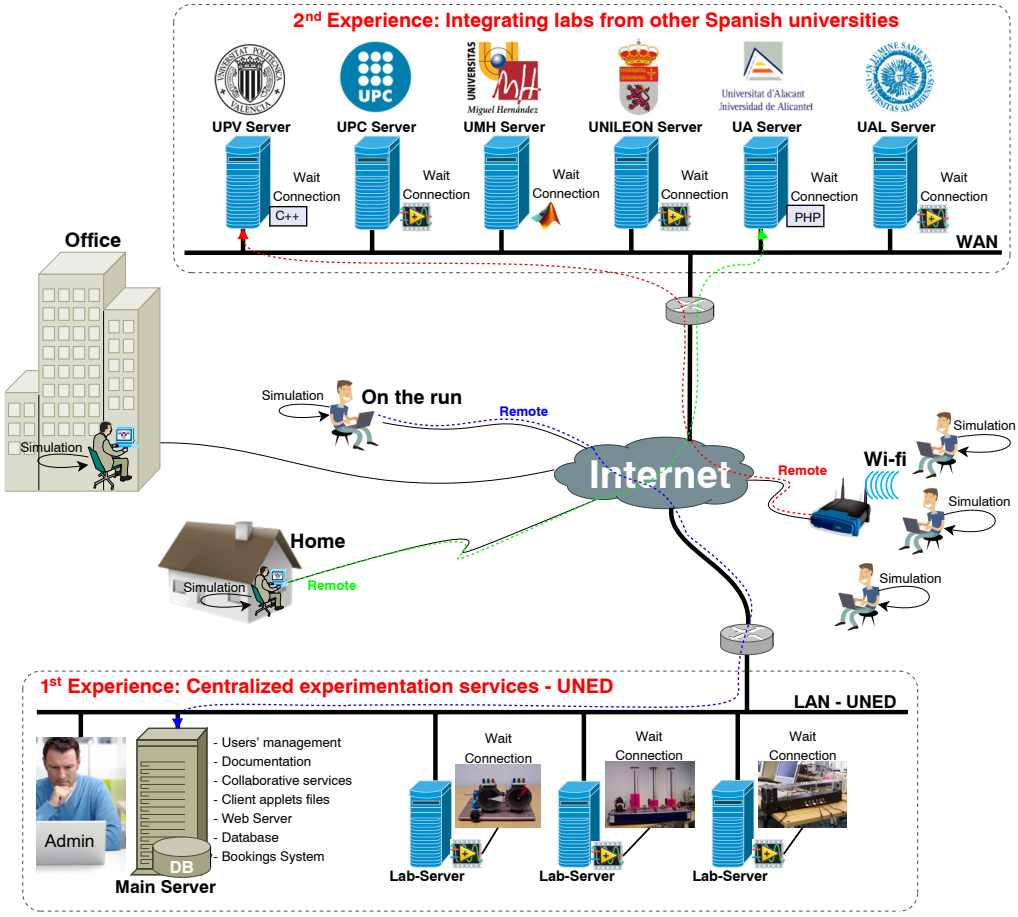


Figure 8.2: AutomatL@bs project network.

2. To develop a virtual and remote control laboratory based on standard established in this dissertation.

3. To generate all the necessary documentation for the laboratory such as an explanation of the *Ejs-based* GUI, tasks protocol, and practical guides for students to complete activities independently.

4. To keep the plants in an operative state during the execution period of the practical activities.

5. To answer students' questions regarding the laboratory tasks (and/or experiments) they are working on.

6. To evaluate reports written by students.

These remote-labs were offered to a total of 112 Master students in engineering schools coming from the other universities. Students from each university worked

on three of the nine remote systems available offered by the AutomatL@bs project (one plant from their university + two plants from other locations).

Unlike the UNED, the teaching methodology of the other academic centres focused on face-to-face hands-on activities in the presence of a teacher assistant. For this reason, some live demonstrations taking place during classroom sessions on the use of the remote experimentation interface were completed by teaching assistants. Then, students were required to use the system to get a fluent handling of the interfaces. Finally, and after several sessions, they could complement their work by using the web-based experimentation system of **AutomatL@bs**.

UNED students were first offered the possibility of accessing the systems available at the UNED (the *DC motor*, the *heatflow system*, and the *threetank system*) and, could then complete their work remotely through the Internet. During these experimental sessions, students could save data measurements and parameters, which they used later to write their final reports. These reports were placed by students in the eJournal space for a post evaluation. Teaching assistants from each university taking part were in charge of completing this task.

8.2.1 Access to AutomatL@bs

Figure 8.3 shows the website whereby students access to the experimentation system. It provides information on the whole system, the processes available, the network's virtual and remote laboratories, etc. The purpose of this information is to introduce students to the virtual experimentation before working with the real processes.

As mentioned before, teachers and students from other universities took part in this second evaluation of the environment. The main aims of this study were:

a. To enable students to access other practical experiments not available at their universities and,

b. To increase the quality and robustness of the network of virtual and remote laboratories for a higher number of students and teachers with different teaching concerns.

Figure 8.3: AutomatL@bs home page.

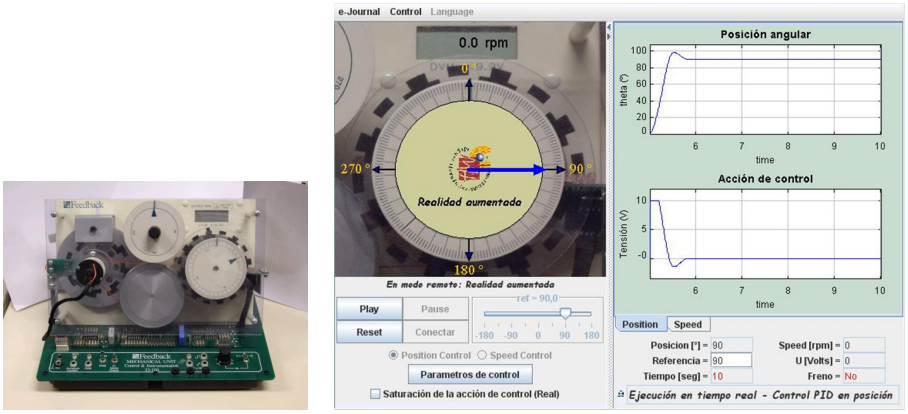
8.2.2 Remote systems available

In addition to the prototypes presented in this thesis, each university participant provided a physical plant. A brief description of the remote systems available in the **AutomatL@bs** project are presented hereafter.

DC motor: "Miguel Hernández" University of Elche

The Direct Current Motor is one of the classical experiments in automatic control laboratories. It allows to study the dynamic behaviour of a motor fed by a direct current source (see Figure 8.4) with regards to *speed* and *position*. The DC Motor is a common actuator in control systems and therefore, although it is a simple and straightforward example, it requires special attention.

The didactical setup is an electromechanical process intended to perform the angular position or speed control of a load using the direct current supplied to the motor as a manipulated variable (Costa-Castelló et al. 2010).

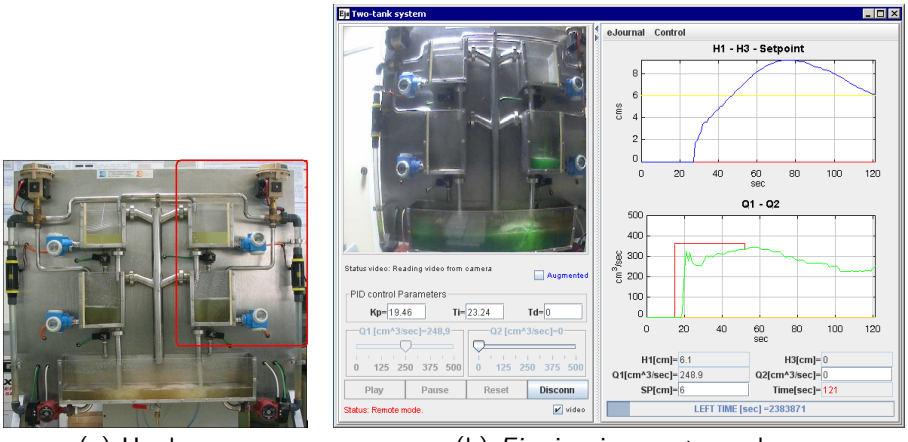


(a) Hardware. (b) *Ejs* view in remote mode.

Figure 8.4: DC motor: Miguel Hernández University.

One tank system: University of Almería

The four-tank system represents one of the most complete processes to teach automatic control concepts (Johansson 2000, Dormido & Esquembre 2003). It can be configurated to enable the study of monovariable and multivariable systems. In this case, the plant is configured as a two-tank system (see Figure 8.5(a)) which objective is to control the liquid level in the lower tank, using the upper tank to induce disturbances (Guzmán et al. 2007a,b, 2010).



(a) Hardware. (b) *Ejs* view in remote mode.

Figure 8.5: One tank system: University of Almería.

Roto-magnet system: Polytechnic University of Catalonia

This plant was conceived and designed to analyze control problems linked to the frequential response of linear systems (see Figure 8.6). The process allows to

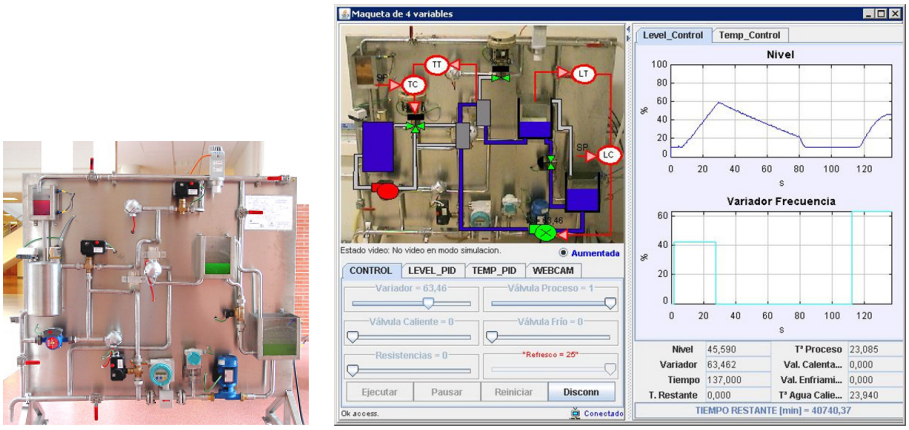
(a) Hardware. (b) *Ejs* view in remote mode.

Figure 8.6: The Rotoiman system: Polytechnic University of Catalunia.

observe the effect of disturbances caused by certain frequencies on the system's output and validate different control techniques as resonant or repetitive control strategies (Diaz et al. 2009, Costa-Castelló et al. 2010).

Four variable system: University of León

The four-variable system is a multifunctional industrial equipment designed and developed by the *Automatic Control Group* of the University of León (Figure 8.7). The plant allows to operate basic and advanced control experiments on the following variables: flow, pressure, temperature (cooling and warming circuits), and level. It also incorporates industrial instrumentation, neumatic, and electrical actuators for valves with variable frequency in the pumps (Guzmán et al. 2010).

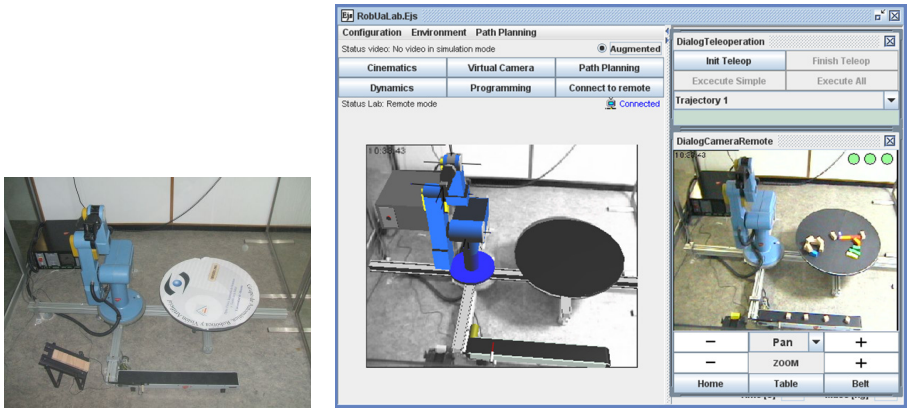


(a) Hardware. (b) *Ejs* view in remote mode.

Figure 8.7: Four variable system: University of León.

Robot arm: University of Alicante

Using this laboratory enables to control a robot arm to plan and track trayectories (see Figure 8.8). The virtual lab allows to work on a 3D representation of the Scorbot ER-IX robot arm located in the University of Alicante. The simulation represents the real movement of the robot arm as realistically as possible. Students can design simple and complex trayectories and analyze the dynamic behaviour of the response (Jara et al. 2008, 2009b).

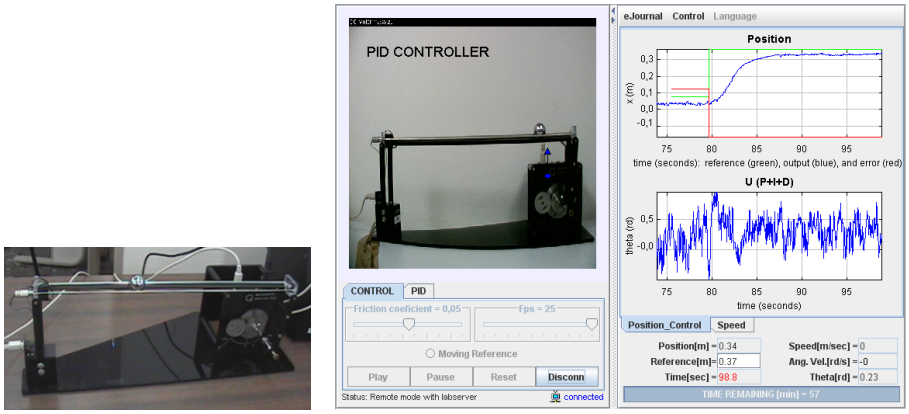


(a) Hardware. (b) *Ejs* view in remote mode.

Figure 8.8: Robot arm: University of Alicante.

Ball and beam system: Polytechnic University of Valencia

This system enables to obtain the position control of a ball rolling on a beam with horizontal movement (see Figure 8.9). The beam inclination angle is controlled



(a) Hardware. (b) *Ejs* view in remote mode.

Figure 8.9: Ball and beam system: Polytechnic University of Valencia.

with the voltage applied to the motor that is mechanically coupled to its mobile end. In this case, this system had the server side programmed in C++. This means, the remote connection between *Ejs* programs (Java) and C++ had to be solved (Diez et al. 2009, Costa-Castelló et al. 2010).

The following section presents a brief analysis of the results obtained from this last system evaluation experiment involving the integration of remote labs from other academic institutions around Spain.

8.2.3 Analysis of results

A collection of statistical graphs summarizes results obtained in the evaluation process. Figure 8.10 shows a general view of the level of the students' satisfaction during the practical experiences. 19% of them answered that they strongly agreed and 69% agreed with the use of the system. Moreover, other questions about the advantages that students/teachers expected when using remote experiments in the educational process were reported. The results obtained were that the use of new technologies, specially the Internet, encourages students to do most of their practical exercises with the help of these resources.

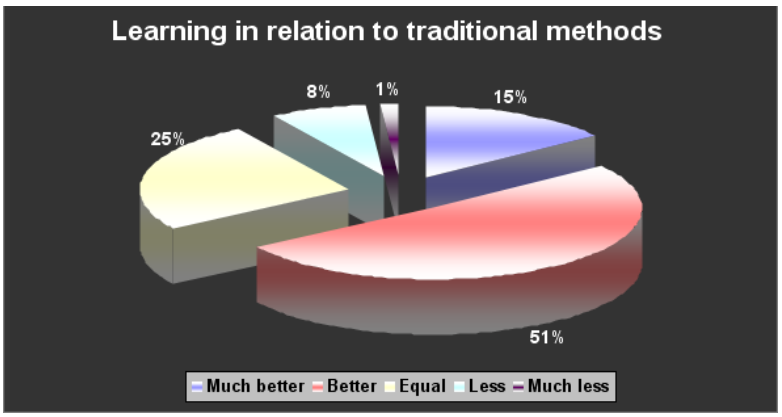
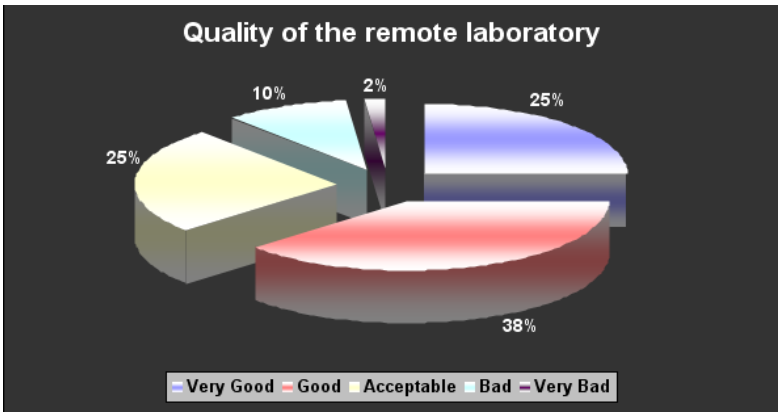
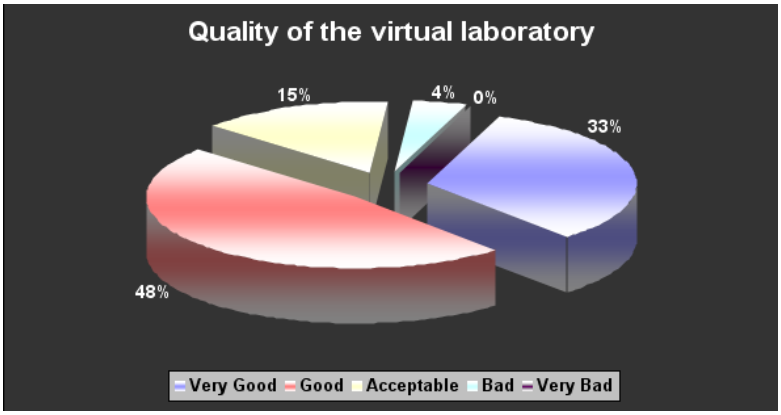


Figure 8.10: Satisfaction enquiry about the practical activities.

Figure 8.11(a) and Figure 8.11(b) give comparative information about how learning improved when using these new technological methods compared to the traditional ones. In most cases, students' disagreement (around 9%) is due to the fact that they did not have the chance to experiment directly with the real equipment.



(a)



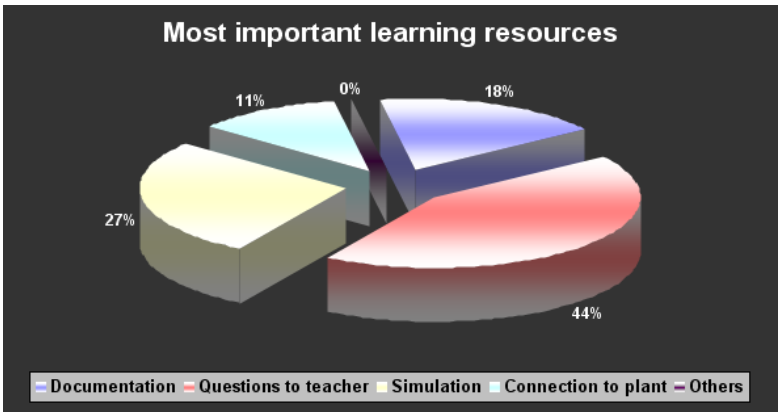
(b)

Figure 8.11: Regarding the overall system.

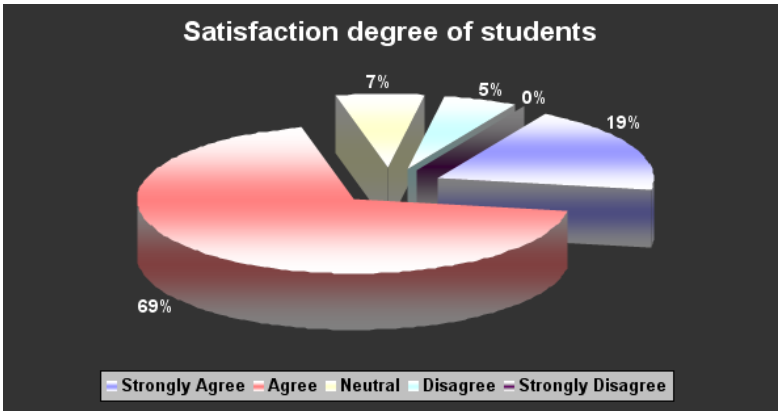
A solution to this problem is to follow an educational methodology based on the "blended learning" concept. That is, to first carry out face-to-face classes where students can interact and experiment "in-situ" with the real plant and, to enable them afterwards to have access to the experimentation environment to complete their practical exercises at a distance.

With regards to the quality of virtual and remote laboratories, most students expressed a positive opinion about its development in terms of user functionality (see Figures 8.12(a) and 8.12(b)).

Negative opinions were a consequence of the bad quality of the Internet connections established. *Ejs* presents great advantages compared to other software alternatives to develop the client side interfaces for remote experimentation. The high degree of acceptance was because of the quality of the applications, in particular, the simulations which represent almost faithfully the real aspect of the



(a)



(b)

Figure 8.12: Quality of the web-based laboratories.

didactical setups located in the university laboratories. This is a very important aspect since students get a first insight of the systems through the work they complete in virtual mode and therefore, the simulations behaviour should match real counterparts as much as possible.

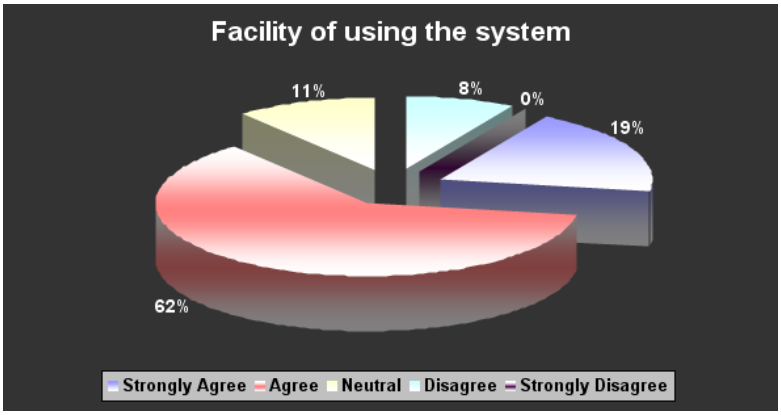


Figure 8.13: The most important learning resource.

Finally, Figure 8.13 shows how questions and the documentation needed for practical exercises are essential for the student's performance. In fact, students felt more comfortable when they were accompanied by a teacher, in this case, in a virtual way, by using the web resources provided by eMersion.

8.3 Conclusions

In this chapter, two pilot experiences carried out with the remote experimentation system developed in this dissertation have been presented and analyzed: the UNED pilot experience and the AutomatL@bs project. The set of remote labs integrated into the remote experimentation system of the AutomatL@bs project has been also described.

Student's perception was analyzed during the academic years 2006-2007 (UNED pilot experience) and 2007-2008 (AutomatL@bs project). In both tests, the results show a high degree of satisfaction which demonstrates that the approach presented was correctly developed.

The information extracted from these studies will be used to improve the quality of the web-based experimentation system. New functionalities or the improvement of existing ones must be achieved according to the results obtained in these evaluation processes.

9

Conclusions and Future Research

9.1 Conclusions

General conclusion

Virtual and remote experimentation for engineering education can be considered as a mature technology. However, the process of transforming a classical control experiment into an interactive web-based laboratory is not an easy task. This dissertation provides a systematic approach (experimentation and e-learning layers) for the fast development of remote laboratories using three tools: *Easy Java Simulations*, *LabVIEW*, and *eMersion*. The approach suggested eases the development of online experimentation environments and, it also provides an effective scheme to switch between simulation and tele-operation of real systems, a key feature for hands-on learning activities in engineering education.

Specific conclusions

The "JiL Server" methodology proposed in Chapter 3 to create web-based laboratories (experimentation layer) and the developed software tools were successfully applied to develop the following web-based remote and virtual laboratories for control education:

- Virtual and remote lab of a DC motor, a temperature control system, and a coupled threetank system in the Automatic Control Laboratory of the Department of Computer Science and Automatic Control of the UNED.

- Virtual and remote lab of a one-tank system located in the Department of Computer Science and Languages of the University of Almería (UAL).

- Virtual and remote lab of a "roto-magnet" system controlled by magnetic fields located in the Department of Systems Engineering and Automatic Control of the Technical University of Cataluña (UPC).

- Virtual and remote lab of a four variable system, a multifunctional industrial equipment designed and developed by the Automatic Control group of the University of León (UNILEON).

eMersion as software tool for publishing remote and virtual-labs covers all the design requirements of the e-learning layer. Specifically:

- eMersion allows to maintain the pedagogical aspects of interaction and collaboration of traditional hands-on laboratories when moving towards a flexible learning model based on the Internet.

- eMersion organizes and puts all the complementary learning resources to use virtual and remote labs at the disposal of students. User's manual, theory, assignments, task protocols, and a complete instruction manual of the global system are available at the experimentation environment. Furthermore, the *eJournal* provides a shared space where students can save and organize the results of their practical activities, and collaborate amongst them and with their teachers.

The automatic bookings system was successfully integrated into eMersion and used by students when they perform their practical activities. The application design suggested helps to optimize the use of physical resources available by including:

- A simple mechanism to book resources to work on the real systems located in the laboratory.
- A straightforward module of encriptation and user authentication.
- A centralized backup for bookings.
- E-mail notifications of new reservations and/or cancelations.

Finding out about students' perception during the learning process is a very important matter to assess an experimentation environment as a valuable learning/teaching tool. For this reason, during the two pilot experiences carried out with students (UNED pilot experience and AutomatL@bs project) students were asked to fill out an evaluation questionnaire to determine the pros and cons of the experimentation environment. Such results encouraged us to repeat the experience involving more students and university groups.

The AutomatL@bs project presented in Chapter 8 is the most recent research result and it demonstrates its benefits over the last three academic years in the universities that took part in the project. Results from the previous evaluation will let us debug and improve the framework in different directions. First, the number and variety of physical processes will be increased by enrolling new universities to the AutomatL@bs project. Also, we will try to let students carry on with their practical experiences using other devices (mobile phones, PDAs) and user interfaces (e-mail, web forms, HTML/Javascript thin interfaces, etc.).

9.2 Future work

Finally, some ideas about possible extensions of this work are the following:

1. The notion of *smart objects* discussed in (Thompson 2005, Salzmann & Gillet 2008, Johnson et al. 2009) is pursued in the following two points. This idea can be applied in remote experimentation topics by increasing the intelligence of the server-side applications, i.e., by extending the capabilities of JiL Server.

- To include new functionalities to the JiL Server application in order to improve the maintenance of laboratory equipments. In this sense, administrators could benefit from implementing automatic fault notification mechanisms via email or mobile messages, statistic tracking of connections, state notification, etc.
- To add new communication protocols to the JiL Server approach in such a way that it allows web-clients developed with other technologies control the devices remotely. This would allow to make a simple mashup of these applications with other web enviroments (Ngolo et al. 2009, Vargas et al. 2009c).

2. It would be very interesting to modify the current remote-labs prototypes, in which the structure of the controller is already predefined, towards a more flexible structure where students can define the controller form. This idea is pursued in the next point. Some examples supporting this working line can be found in (Farias et al. 2009).

   - To extend the virtual and remote control laboratory prototypes developed throughout this dissertation by including new control algorithms and even, by offering students the opportunity to test their own implementations. Thus, these hands-on laboratories through the Internet could be applied to courses in higher degrees (Master or PhD programs).

3. eMersion capabilities can be enhanced by means of integrating external web applications. Two new modules could be developed and included in order to improve students' motivation in the completation of their remote working experience. These ideas were taken from (Gillet et al. 2005, Salzmann et al. 2008).

   - To include a new web module into eMersion that would allow students to carry out the analysis and design of controllers on-line. They can use tools such as Matlab/Simulink or Scilab to perform these activities

currently. This means, we can close the instruction cycle, the experimentation phase, the analysis process, and the design by using just the web browser, avoiding the use of standalone applications or the purchasing of licenses.

– To develop a web module to eMersion that includes awareness tools. Students could then track their own progress and, they could compare the progress they have made with other classmates. This development would also allow to balance the workload of the system, that is, students could start their work earlier (compared to other students), avoiding the high demand of students at the end of the course.

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APPENDICES

A

Modelling and Control

This appendix describes the modelling and control strategies applied in the development of the virtual and remote control laboratories presented in Chapter 4 of this thesis. First one, the mathematical model of the system is introduced. Second one, simple PI controllers have been obtained for each process based on these models. Finally, tracking references and performance tests to demostrate the reliability of controller designs are presented.

Note: The information provided in the next sections have been used for developing the simulations and local control VIs of each didactical-setup.

A.1 The Three-tank system: Modelling and control

A.1.1 Modelling

The model obtained through physical relationships of the variables is first described. Mass balance equations and *Torricelli's law* are here applied. Next, we complement the modelling of the process obtaining a non-parametric representation of the system (transfer functions) through identification techniques.

Mathematical model

The mathematical model of the process is described by the following balance equations:

$$A\frac{dh_1}{dt} = Q_1 - Q_{13} - Q_{1leak} \tag{A.1}$$

$$A\frac{dh_3}{dt} = Q_{13} - Q_{32} - Q_{3leak} \tag{A.2}$$

$$A\frac{dh_2}{dt} = Q_2 - Q_{32} - Q_{20} - Q_{2leak} \tag{A.3}$$

where t represents time, h_1, h_2, and h_3 correspond to the liquid level in each tank, A represents the tanks cross sections, Q_1 and Q_2 denote the flow rates of pumps 1 and 2, Q_{ij} denotes the flow rates between tank T_i and T_j ($j = 0$ represents the system's output), and Q_{ileak} ($i = 1, 2,$ or 3) represents the flows that leave the $tank_i$ when its drain valve is open. These three balance equations mean that the volume variation in each tank is equal to the sum of the flow rates that enter and leave the tank.

Yet flows Q_{13}, Q_{32}, and Q_{20} are still unknown in Equations 1, 2, and 3. To obtain them, we use *Torricelli's law*:

$$Q_{ij} = az_i \, S_n \, sgn(h_i - h_j)\sqrt{2g|h_i - h_j|} \tag{A.4}$$

where az_i is the outflow coefficient, $sgn(x)$ is the sign of the argument x, and g is the acceleration due to gravity.

The resulting equations to calculate the partial flows are thus,

$$Q_{13} = az_1\ S_n\ sgn(h_1 - h_3)\sqrt{2g|h_1 - h_3|} \tag{A.5}$$

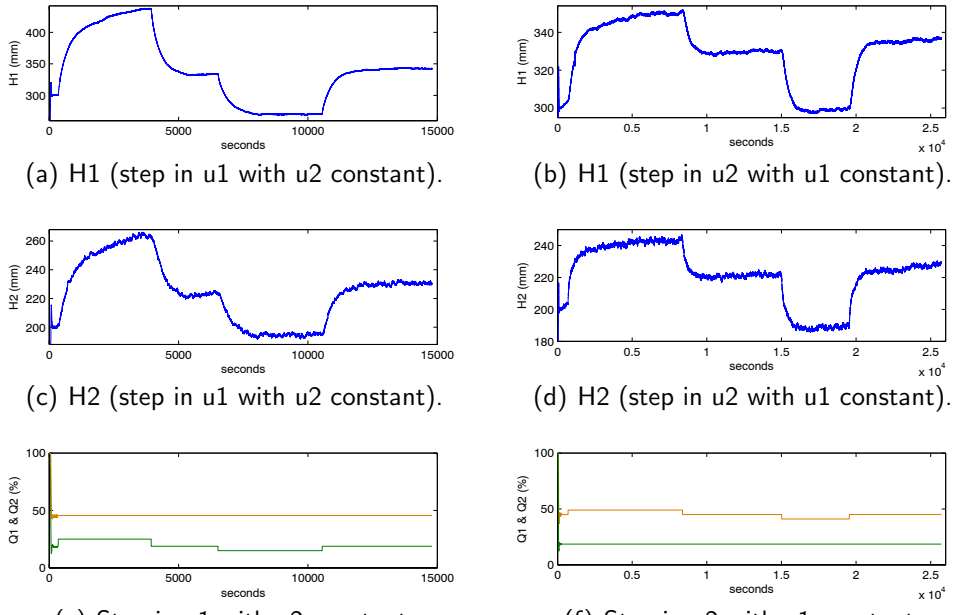
$$Q_{32} = az_3\ S_n\ sgn(h_3 - h_2)\sqrt{2g|h_3 - h_2|} \tag{A.6}$$

$$Q_{20} = az_2\ S_n\sqrt{2gh_2} \tag{A.7}$$

The valves of the pipe connections, the pumps, and the leaks have been modeled with the relationships which can be found in (Shinskey 1996). The value of the physical parameters of the process are provided in the Appendix B.

Identification process

To get a description of the process by transfer functions, it is neccesary to make the identification from experimental data. To get the experimental data, different open loop experiments with the actual three-tank system were done. The identification of the process is done around the normal operating point. In this case, the experiences have been done around the following working point in steady state: Q1% = 19.56, Q2% = 43.24, H1 = 300 [mm] and H2 = 200 [mm].



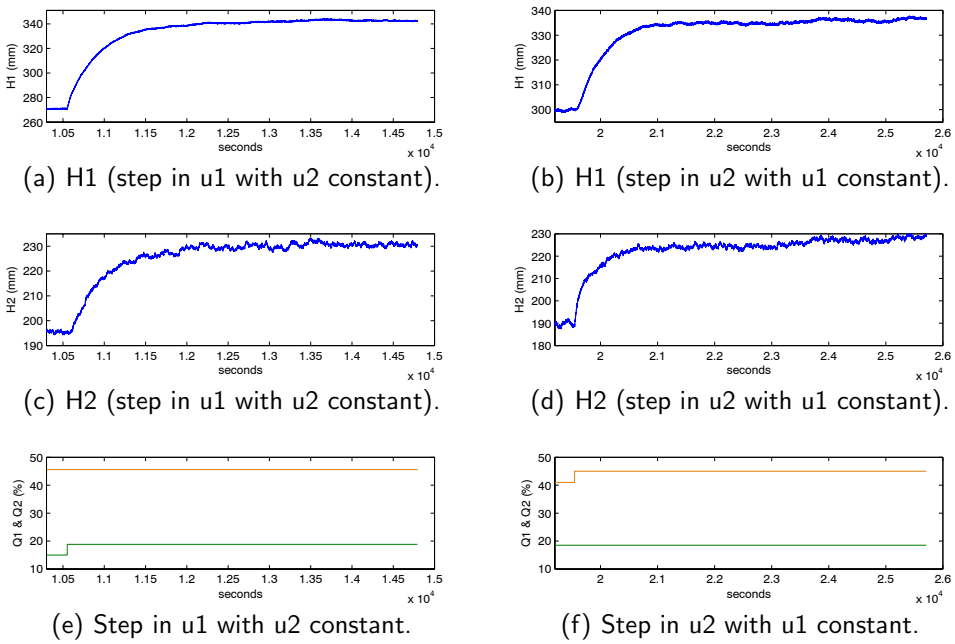
(a) H1 (step in u1 with u2 constant).
(b) H1 (step in u2 with u1 constant).
(c) H2 (step in u1 with u2 constant).
(d) H2 (step in u2 with u1 constant).
(e) Step in u1 with u2 constant.
(f) Step in u2 with u1 constant.

Figure A.1: Open loop experiences for identification.

Figure A.1 depicts six graphics. The plots corresponding to the first column show the temporal response of the variables to control (levels in tank 1 and tank 2) when an input step is applied to the first manipulated variable (pump 1) while the second one (pump 2) is kept constant. In the same way, the three graphics of the second column show the evolution of these variables when the input step is applied to the second manipulated variable (pump 2) while the first one (pump 1) remains constant.

It is possible to appreciate that the system presents a similar response to a first order system with delay and therefore, a model with these characteristics should be fit to provide a non-parametric description (by means of transfer functions) of the system (Figure A.3).

Based on the above mentioned, the value of the parameters calculated for the non-parametric description of the process have been obtained by analyzing the last step change of the overall time window.



(a) H1 (step in u1 with u2 constant). (b) H1 (step in u2 with u1 constant).

(c) H2 (step in u1 with u2 constant). (d) H2 (step in u2 with u1 constant).

(e) Step in u1 with u2 constant. (f) Step in u2 with u1 constant.

Figure A.2: Temporal window to calculate of the model parameters.

From data in Figure A.2, it is possible to get the parameters of the first order transfer functions that relate the action of each of the pumps with the liquid levels inside the tanks T_1 and T_2, i.e., the representation in blocks diagram of the process such as is shown in Figure A.3.

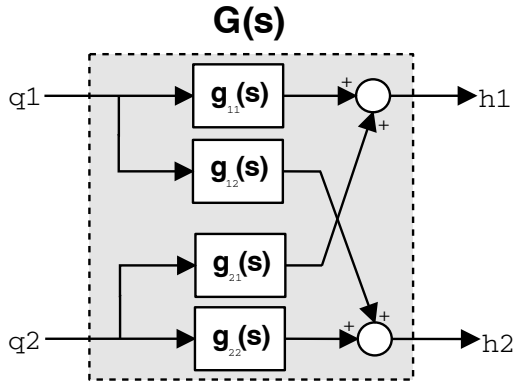


Figure A.3: Three-tank system representation by transfer functions.

Table A.1 contains the first order model parameters for each transfer function.

Table A.1: Parameters obtained from the identification process.

$g_{ij}(s)$	T_0(seconds)	T_p(seconds)	K(cm/volts)
$g_{11}(s)$	0	405	2.4
$g_{12}(s)$	46.5	475.5	0.925
$g_{21}(s)$	49.5	400.5	1.167
$g_{22}(s)$	0	364.5	0.95

Finally, the description by means of transfer functions is shown in the equations A.8 and A.9:

$$H_1(s) = \frac{2.4}{405s+1}Q_1(s) + \frac{0.925e^{-46.5s}}{475.5s+1}Q_2(s) \tag{A.8}$$

$$H_2(s) = \frac{1.167e^{-49.5s}}{400.5s+1}Q_1(s) + \frac{0.95}{364.5s+1}Q_2(s) \tag{A.9}$$

A.1.2 Multivariable control

From a practical point of view, we can run controllers in two different modes: *manual* or *automatic*. In manual mode, the operator directly manipulates the controller output, typically by moving sliders that increase or decrease it. In automatic mode, a computer or some other automatism generates the controller output signals. Manual mode is most useful during the plant's startup and shutdown or in an emergency situation. Conventional controllers have a manual/automatic switch to transfer the controller from automatic mode to manual.

Interaction study of the variables

Before addressing the design of controllers to be used in automatic mode, a variables interaction study has been done. A multivariable system has a set of input and output variables which can be coupled with each other. We talk about *coupling* among variables when the change in one input variable affects to more than one output variable. Hence, by studing the degree of interaction among variables, we can decide both the variables pairing and the control strategy.

To analyze both pairing and interaction variables, it is neccesary to get the steady state gain matrix $SSGM$ and the relative gain array RGA (Morilla 2005, Vásquez & Morilla 2002). For the system under study, the calculus of the SSGM is carried out by appling limit ($s \to 0$) to the transfer functions which relate the input flows Q1 and Q2 with the liquid levels H1 and H2 (see equations A.8 and A.9). Thus, the SSGM obtained is:

Table A.2: SSGM for the threetank system.

$SSGM_{threetank}$	**Q1**	**Q2**
H1	2.4	0.925
H2	1.167	0.95

To get the RGA, the following relation for $n \times n$ systems (same number of input and output variables) is used (Bristol 1966):

$$rga = ssgm. * (inv(ssgm))' \tag{A.10}$$

By replacing the SSGM in the equation A.10, we get the RGA:

Table A.3: RGA for the threetank system.

$RGA_{threetank}$	**Q1**	**Q2**
H1	1.9	-0.9
H2	-0.9	1.9

According the *pairing criteria* based on RGA, each output should be paired with the input that presents the relative gain closest to unity, avoiding any pairing with negative relative gain. Thus, by observing this matrix, the best pairing to

get the less interaction degree between control loops would be: controlling H1 with Q1 and H2 with Q2.

On the other hand, it is necessary to verify whether pairing causes unstability in closed loop. The Niederlinski theorem (Niederlinski 1971) is used to check the stability of the system in closed loop. The theorem postulates: "The final closed-loop system obtained from pairing $u_1 - y_1$, $u_2 - y_2$, ..., and $u_n - y_n$, for a $n\ x\ n$ process is unstable if the cocient between the SSGM determinant and the product of the elements in the diagonal is negative", that is:

$$NI = \frac{SSGM}{\prod_{i=1}^{n} k_{ii}} < 0 \tag{A.11}$$

By using the previous formule for the threetank system, it is obtained:

$$NI_{threetank} = \frac{(2.4 \times 0.95) - (0.925 \times 1.167)}{2.4 \times 0.95} = 0.5265 \tag{A.12}$$

As the NI obtained is positive, we need additional information to guarantee the stability in closed loop. This rule is simple and its use is convenient just steady state information is needed. This information is easily obtained during the design process.

The interaction study of the variables suggests that a *descentralized control strategy* can be applied to control the system.

Decentralized control

A controller objective in our system is to control the liquid level in both T_1 and T_2. From an inspection of the process equations, it seems natural to use the pump flow rate $Q_1(t)$ to control the level in the first tank $h_1(t)$, and $Q_2(t)$ to control $h_2(t)$. In this context, previous variables interaction analysis has demonstrated that such pairing of variables can be applied for controlling the system. This strategy is often called *decentralized control*, which is a simple approach to multivariable controller design in which the matrix transfer function $G(s)$ is a square plant (2×2) to be controlled with a diagonal controller (see Figure A.4).

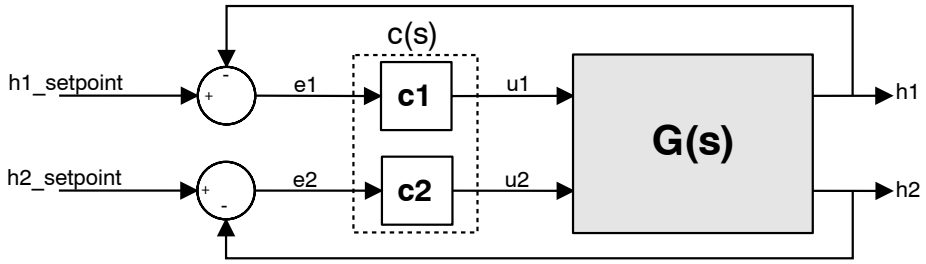


Figure A.4: Descentralized control strategy. $G(s)$ is the three-tank system to be controlled, C(s) is the controller to be designed, and is composed of two elements $C1$ and $C2$. Ci controls the level in tank i. The variables $hi\_setpoint$, ei, ui, and hi are the setpoint to be reached, the error signal, the control signal and the liquid level in $tank\ i$, respectively.

This strategy works well if $G(s)$ is close to diagonal because the plant to be controlled is essentially a collection of independent subplants, and we can design each element in the controller $C(s)$ independently, as indicated in Equation A.13:

$$C(s) = diag\{C_1(s)C_2(s)\} \tag{A.13}$$

A classical and popular technique for designing C1 and C2 is via proportional-integral-derivative (PID) control. A standard PID controller, also called a three-term controller, has a transfer function *C(s)* given by

$$C(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \tag{A.14}$$

where K_p is the proportional gain, T_i the integral time, and T_d the derivative time. For the three-term functionalities,

- the proportional term provides an overall control action proportional to the error signal through the all-pass gain factor;
- the integral term reduces steady-state errors through low-frequency compensation via an integrator; and
- the derivative term improves transient response through high-frequency compensation via a differentiator.

To calculate the PID controller parameters in each loop (SISO tunning), TITO environment (Vásquez & Morilla 2002, 1999) has been used. This tool allows: to

simulate 2 x 2 systems with descentralized control in both open and closed loop with PID controllers, to analyze the performance of the controller design (RGA, DNA, Gain and Phase Margin measurements), and to comparate several designs to choose the most optimal. PI controllers (T_d = 0) were calculated by using a TITO environment for the threetank system.

$$C_1(s) = 3.38(1 + \frac{1}{56.54s}) \; ; \; C_2(s) = 8.54(1 + \frac{1}{50.89s}) \tag{A.15}$$

The controllers in A.15 were obtained for a Phase Margin = 60° in a normal frequency operation range for the system.

Reference tracking and disturbance rejection

Figure A.5 shows the experiment carried out on the threetank system for testing the performance of the controllers in reference tracking (both simulation and real testings). The PI controllers used for testing are the previously calculated (equation A.15).

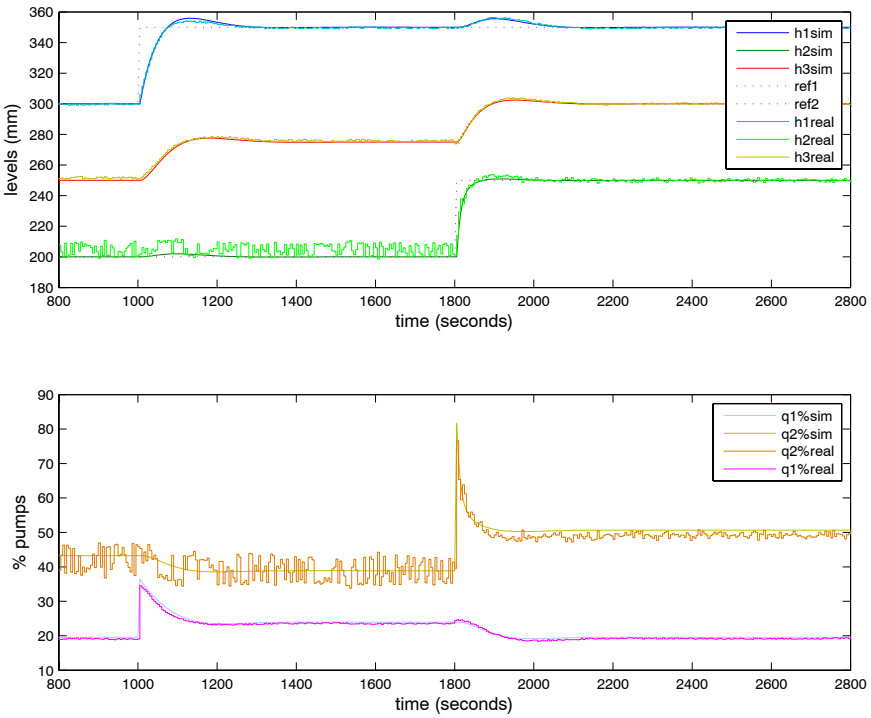


Figure A.5: Tracking references - Three-tank system.

The experiment starts with the tanks in a zone close to the normal operating point ($h1 = 300$ [mm], $h2 = 200$ [mm], $h3 = 250$ [mm]). Then, the reference for the tank 1 is risen until 350 [mm] at $t = 1000$ [sec] and, after that, the reference for the tank 2 is placed in 250 [mm] at $t = 1800$ [sec]. The plots in Figure A.5 show the behaviour of the system under changes in the references in both simulation and real. We can see that the liquid level for the tank 1 and tank 2 track perfectly to the setpoint. Furthermore, the control signals do not reach the pumps saturation for these jumps in the references. Nevertheless, the controllers implement antiwindup techniques in order to counteract this effect when saturation levels are reached.

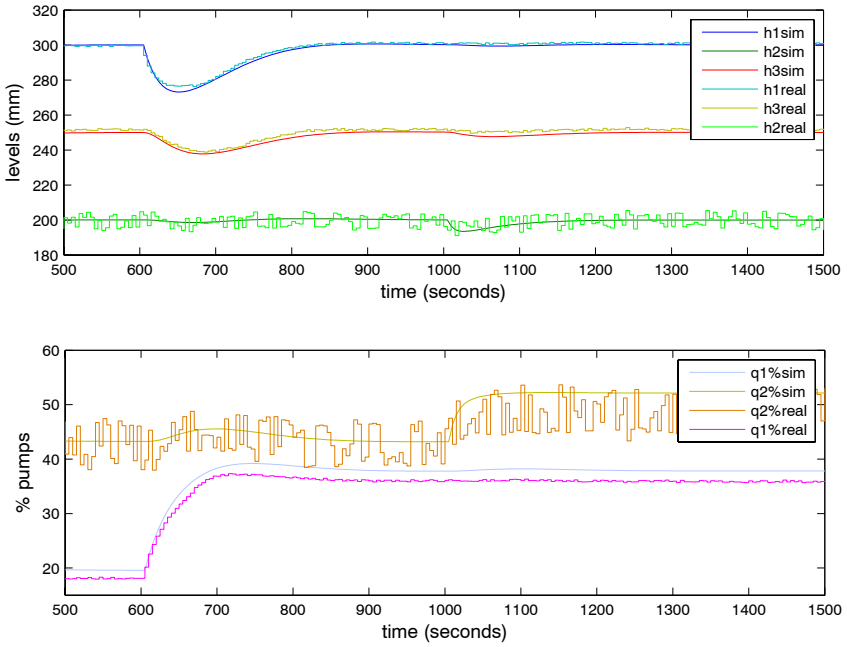


Figure A.6: Disturbance rejection - Three-tank system.

On the other hand, Figure A.6 shows the behaviour of the controllers under these sudden changes in the dynamic of the system (disturbances). The experiment starts around the normal operating point. At time $t = 600$ [sec], the leak valve of tank 1 is opened at 25% and the leak valve of tank 2 is opened at 15% at time $t = 1000$ [sec]. In other words, a disturbance is added to the system at this moment. We observe that controllers are able to keep the liquid levels around the operating point in a reasonable time regardless the disturbances.

A.2 The DC Motor: Modelling and control

A.2.1 Modelling

The apparatus is composed of permanent magnets that provide a constant magnetic field whose value is weak due to the rotor's current remains small. Under this assumption and neglecting the inductance of the coil, the static and dynamic equations that govern the behavior of the engine can be derived.

Mathematical model

The dymanic model of the DC motor is described by a set of variables:

$u(t)$ $[V]$: Voltage applied to the motor.

$i(t)$ $[A]$: Current in the motor.

$\omega(t)$ $[rad/s]$: Rotational speed of the charge.

$M_m(t)$ $[Nm]$: Torque applied to the motor.

Φ $[Vs]$: Constant flow generated by the inductor.

R $[\Omega]$: Resistence in the motor inductor.

K $[Nm/AVs]$: Constant of the motor.

J_d $[Nms^2/rad]$: Intertia of the steel disk (charge).

J_f, J_m $[Nms^2/rad]$: Inertia of the motor brake.

f_f, f_m $[Nms/rad]$: Friction coefficients of the motor brake.

The numerical values of the parameters can be obtained in Appendix B. The voltage supplied to the motor $u(t)$ must be compensated by voltage in the resistence of the inductor $Ri(t)$ and the induced voltage generated by the rotational motion $u_i(t)$:

$$u(t) = R\,i(t) + u_i(t) \tag{A.16}$$

The induced voltage is proportional to the angular speed $\omega(t)$ of the motor:

$$u_i(t) = K_e \, \Phi \, \omega(t) \tag{A.17}$$

where K_e is a constant associated to the motor and Φ the constant flow generated by the inductor.

The torque $M_m(t)$ produced by the engine is proportional to the current passing through it:

$$M_m(t) = K_m \, \Phi \, i(t) \tag{A.18}$$

where K_m denotes a constant. On the other hand, a simple energy balance demontrates that constants K_e and K_m are identical, that is:

$$K_e = K_m = K \tag{A.19}$$

According to the *Newton motion law*, the electromagnetic torque supplied to the motor is given, on one hand, accelerating the engine, the inertia and the driven magnetic brake and, on the other hand, by compensating for the viscous friction of the engine and the magnetic brake (the dry friction is ignored):

$$J\dot{\omega}(t) = M_m(t) - f \, \omega(t) \tag{A.20}$$

where J is the rotational mass inertia, $J = J_m + J_d + J_f$ and f is the total friction, $f = f_m + f_f$.

For the model based on the experimental setup located in the laboratory, the influence of the electromechanical pieces to measure and acting on the motor are taken into account (see Figure A.7):

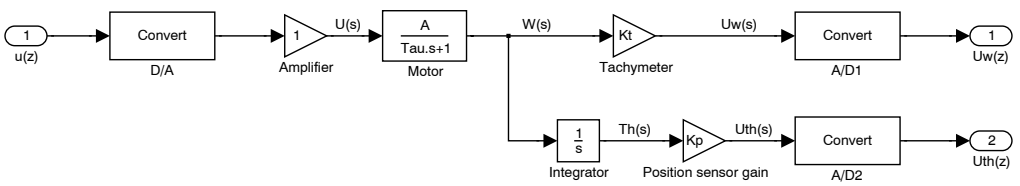


Figure A.7: Model of the DC Motor.

where both the gain A and the time constant τ of the engine can be calculated through the open loop step response of the system in speed. K_t and K_p are the tachymeter and the position sensor constants, respectively.

A.2.2 Design of the PID controllers

Speed control

The DC motor is commonly used in processes where an angular speed is required (for example, in lamination processes). Figure A.8 shows the schematic view of a typical speed control system. The power amplifier receives a direct voltage U that excites an induced magnetic field. The output $U_w(s)$ from the tachymeter is a voltage proportional to the angular speed.

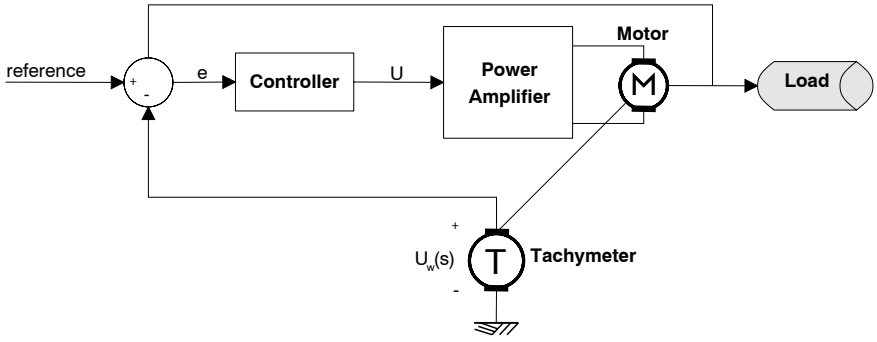


Figure A.8: Typical speed control system.

Figure A.9 illustrates the closed loop control sheme for this process where C represents the controller used to close the loop.

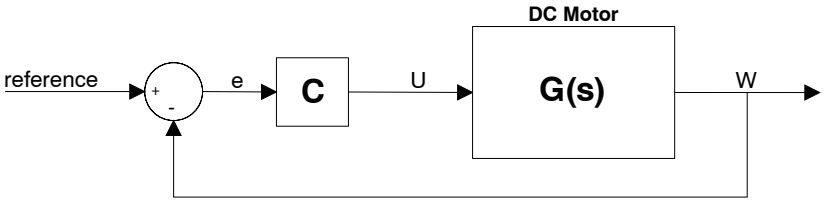


Figure A.9: Control strategy for the DC Motor.

Two control strategies have been developed:

– *Manual controller.* This operating mode allows studying the system response in open loop without control actions. Simply, the changes carried out by users will be directly applied on the system.

– *PI controller.* A PI controller is enough to control the engine speed. Notice that, although the designed controller is a PI, the full PID control algorithm has been programmed to test the effect of a derivative action as well.

The PI controller is as follows:

$$C(s) = K_p\left[1 + \frac{1}{T_i s}\right] \tag{A.21}$$

where:

– K_p is the proportional gain of the controller.

– T_i is the integral time of the controller.

Finally, the closed loop control structure can be seen in Figure A.10.

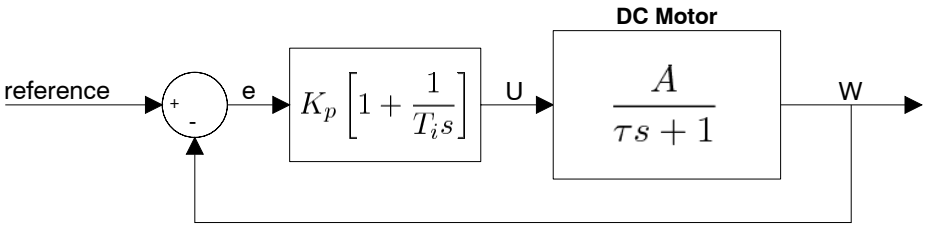


Figure A.10: PI control for speed control on the DC Motor.

As known, if controller parameters are well tuned, the system is stable and non steady state error occurs. In particular, the roots of the system in closed loop (characteristic polynomial - see the equation A.22),

$$s^2 + \frac{1 + AK_p}{\tau}s + \frac{AK_p}{\tau T_i} = 0 \tag{A.22}$$

are responsible of the oscilatory behaviour of the tachymeter output under step changes in the input voltage. Thus, a simple pole placement controller design for first order systems can be applied. With $K_p = 0.08$, $T_i = 0.6$ (for $\tau = 0.253$ [sec] and $A = 27$ [$^\circ/sec \cdot volts$]) a stable behaviour of the system can be obtained.

Position control

In the same way, the motor DC is used also when a fix angular position of the system is requiered. For example, to fix the position a robot arm requieres to

carry out an accurate position control of the engines in the joints. Figure A.11 illustrates a typical scheme of position control with internal feedback of speed in which the output of the position sensor $U_\theta(s)$ is a voltage proportional to the angular position of the motor axis.

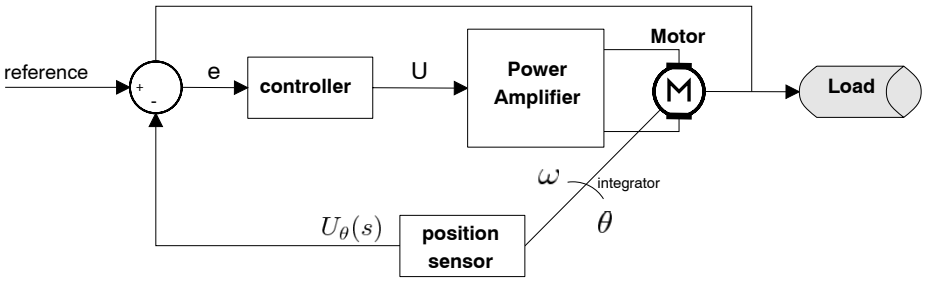


Figure A.11: Typical position control system.

The PI parameters of the system in position control mode can be easily obtained from the scheme in Figure A.12. With K_p = 0.08, T_i = 0.6 a stable behaviour of the system in position control can be obtained.

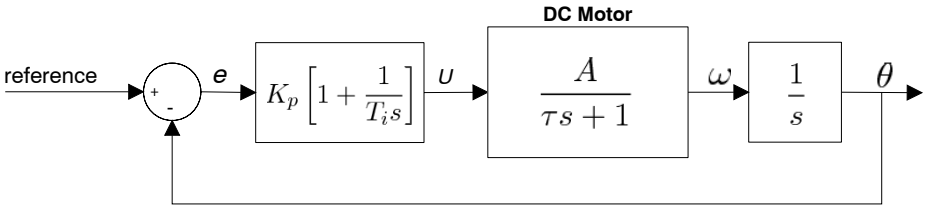


Figure A.12: PI controller for position control on the DC Motor.

Reference tracking

Some experiments for testing the performance of the obtained PI controller parameters in both speed and position control have been carried out. The first experiment starts with the system stabilized around the operating point θ = 150° in position control mode (see Figure A.13). At 60 [sec], the position reference is changed to 200° to observe the dynamic behaviour of the system.

The step response presents an under-damping characteristic with an overshoot of around 21°. The steady state is reached in almost 8 [sec], introducing a second step change at 70 [sec]. Similarly, the steady state in this last test is reached around 8 [sec]. It is also possible to appreciate that in the steady state the motor oscillates slightly around the setpoint. Motors usually present a dead zone due

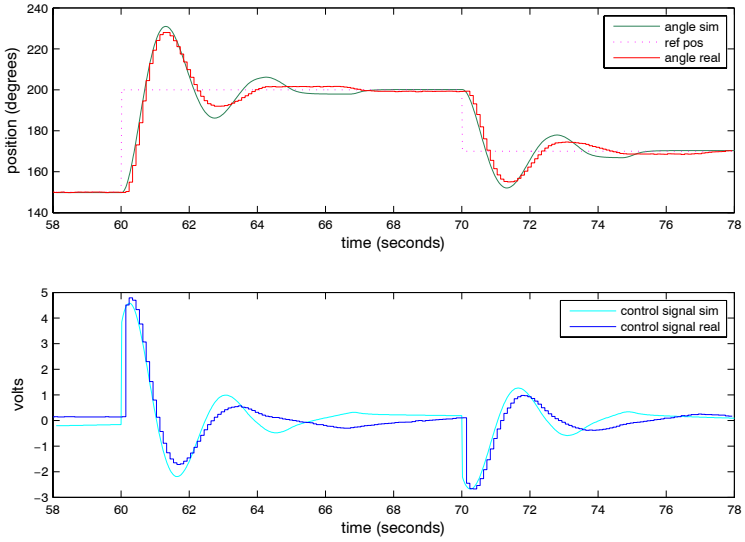


Figure A.13: Tracking reference in position control - DC motor.

to the friction of the mechanism. The dead zone is the input signal range to the motor where no action occurs in the output. The dead zone for our didactical-setup under study is about 0.3 [volts].

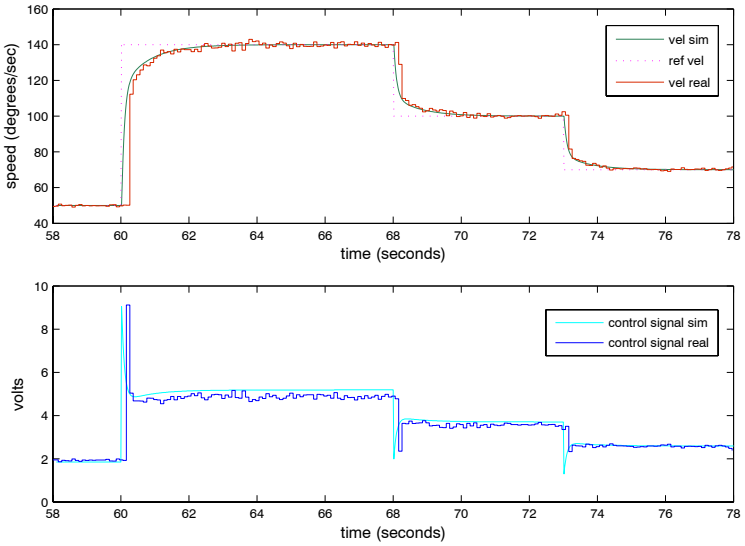


Figure A.14: Tracking reference in speed control - DC motor.

On the other hand, Figure A.14 displays the closed-loop response of the system when controlling speed. The tracking of reference in speed control is a bit simpler than position control because there is not presence of an integrator in the control

scheme. The control parameters has been calculated to get an over-dumped response under step changes in the setpoint. The experiment starts with the system running at 50 [°/*sec*] in steady state. At 60 [sec] the speed reference value is changed to 140 [°/*sec*]. As previously mentioned, there is not overshoot in the response (over-dumped response) and the new setpoint is reached in around 3 [sec]. It also can seen that control signal is not saturated for this range of changes in the references.

A.3 The Heatflow system: Modelling and control

A complete thermodynamic model of the system is difficult to derive. In principle the following equation applies:

$$\dot{T}_n = F(V_h, V_b, T_a, x_s) \tag{A.23}$$

where:

T_n → Temperature at the sensor n

V_b → Voltage applied to the blower

V_h → Voltage applied to the heater

T_a → Ambient temperature

X_n → Distance of the sensor n from the heater

Next sections are aimed to study the dynamic behaviour of the system both in open and close loop. A very simple first order model will be obtained and then, a feedback controller will be developed. In subsequent experiments, research on system identification techniques and control of systems with time delay could be addressed.

A.3.1 Modelling

A simple first order model

To obtain a simple first order model, we can apply step inputs to the heater and observe the temperature change at each sensor.

Figure A.15 shows one of the plots that are obtained. In this case we see the temperature in the three sensors (blue = S_1, green = S_2, red = S_3) with a fixed flow rate using $V_b = 3.0$ [Volts] and three different voltages applied to the heater.

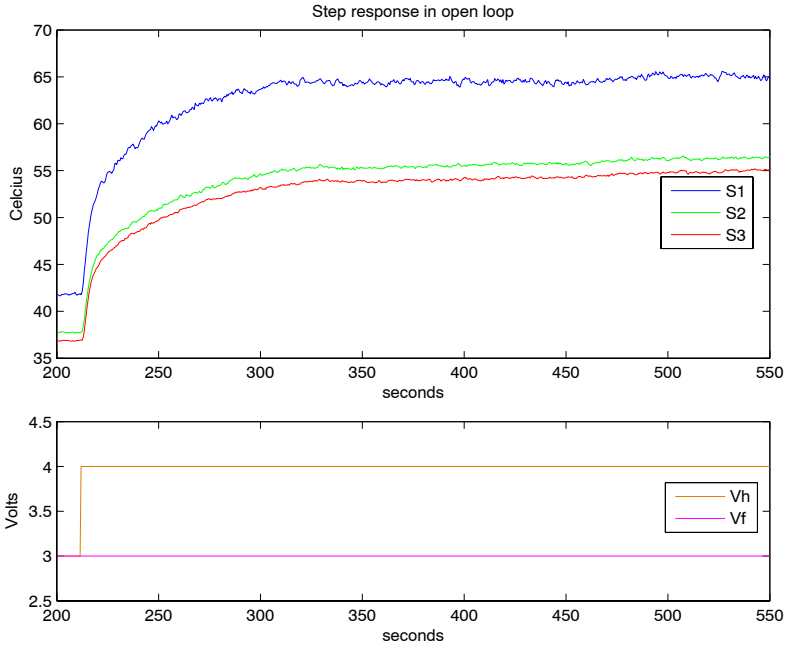


Figure A.15: Step responses at the three sensors when V_h goes from 3 to 4 [volts] and a fan fixed flow rate voltage of 3 [volts].

To design a feedback controller to control the temperature at a desired sensor location, we need to have a model of the system. Examining Figure A.15 we note that the step response can be approximated by a simple first order system of the form:

$$\frac{T_n}{V_h} = \frac{G}{\tau_n s + 1} \tag{A.24}$$

Now suppose we want to control the temperature at S_1 with a fixed flow rate using $V_f = 3$. Examining Figure A.15 we note the following:

Applying $V_h = 4$ [volts] to the heater results in a temperature change of approximately 21.5 degrees (65.5 - 44). The time constant is the elapsed time to reach a 63.2% of the total change. In this case that would be approximately 44+0.632*21.5 = 57.588 degrees (approximately). Examining the figure we see that 57.588 degrees is reached in about 17.9 seconds from the time when the step input is applied ($t = 212$ [sec]).

So a simple first order approximation for the open loop model is:

$$\frac{T_1}{V_h} = \frac{21.5}{17.9s + 1} \tag{A.25}$$

The same procedure should be followed to get a simple first order model for sensors 2 and 3.

A.3.2 Controller design

Now, the design of a feedback controller to regulate T_1 with zero steady state error will be addressed. Notice that the procedure for designing controllers for sensors 2 and 3 should be the same.

The controller is a simple PI of the form:

$$V_h = K_p(T_{1ref} - T_1) + \frac{K_i}{s}(T_{1ref} - T_1) \tag{A.26}$$

Substituting into the first order model we obtain the closed-loop transfer function:

$$\frac{T_1}{T_{1ref}} = \frac{G(K_p s + K_i)}{s^2\tau + (K_p G + 1)s + GK_i} \tag{A.27}$$

The denominator can be rewritten as follows:

$$s^2 + \frac{(K_p G + 1)s}{\tau} + G\frac{K_i}{\tau} = s^2 + 2\xi\omega_0 s + \omega_0^2 \tag{A.28}$$

In this way, we can now obtain the gains K_p and K_i for a desired performance. If we want to specify a *peak time* and *damping ratio* the following equation can be applied:

$$T_{peak} = \frac{\pi}{\omega_0\sqrt{1-\xi^2}} \tag{A.29}$$

By replacing equation A.29 in equation A.28, the gains for the PI controller obtained are:

$$K_p = \frac{2\xi\pi\tau - T_{peak}\sqrt{1-\xi^2}}{GT_{peak}\sqrt{1-\xi^2}} \tag{A.30}$$

$$K_i = \frac{-\pi^2\tau}{GT_{peak}^2(-1+\xi^2)} \tag{A.31}$$

In order to set the gains K_p and K_i, a *damping ratio* $= 0.4$ and a *time peak* $= 12$ can be used to compute them. Thus, the PI control parameters are: $K_p = 0.1437\ [V/deg]$ and $K_i = 0.0679\ [V/(deg \cdot sec)]$.

Reference tracking

A simple experiment to show the performance of the PI controller designed for the control around sensor 1 has been carried out (see Figure A.16).

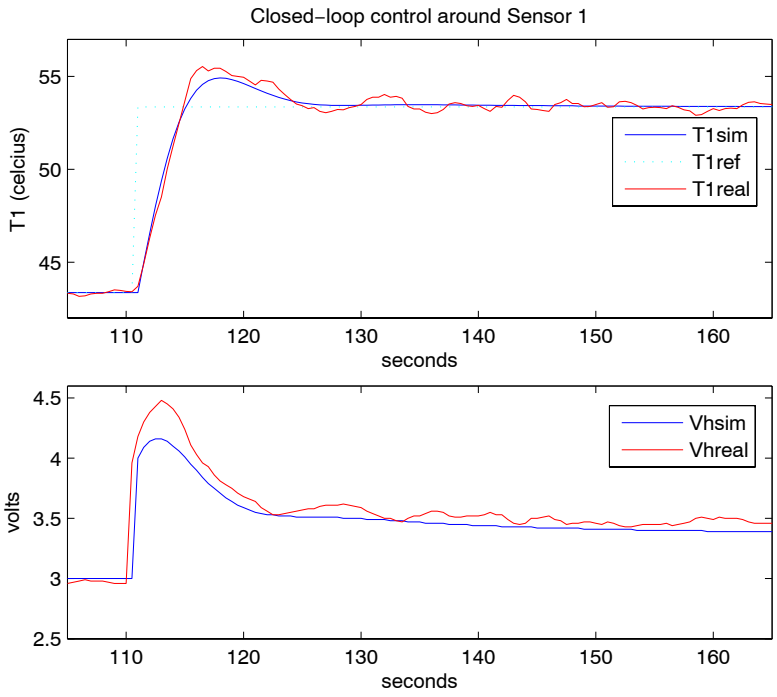


Figure A.16: Tracking reference closing the loop around sensor 1 (constant voltage applied to the blower of 3 [volts]).

The experiment starts with the system stabilized around the operating point $T_1 = 43$ [$^\circ C$] and $U = 3$ [volts] (see Figure A.16). At 110 [sec], the temperature reference T_{1ref} is changed to 53 [$^\circ C$]. We can observe that the behaviour of the system both in simulation and remote mode are similar for the set of control parameters obtained during the designed process. The system reaches the steady state in almost 20 [sec] (without saturation of the control signal) which is according to the performance requirements. It is also possible to see that practically there is not delay between the change of the reference and the control action. The effect of delays can be better appreciated when performing control around the sensor 3 because its location is farther from heater and hence, a small lag between the control action and its effect over the system can be observed.

B

Hardware Description

This appendix provides practical information about the hardware of the didactical-setups presented in Chapter 4 of this dissertation. Furthermore, the technical features of the DAQ boards used to sense/actuate on the mechanisms from a LabVIEW program will be described. In this context, three different DAQ boards have been used to control the plants in the lab: the DAQ-MF614 (from HUMUSOFT s.r.o.), the DAQ-Q8 (from Quanser Consulting) and DAQ-NIPCI6221 (from National Instruments). While the last one can be accessed by using the LabVIEW native driver library (DAQmx), the second one uses the propietary LabVIEW driver software supplied by the provider. In the particular case of the DAQ-MF614, the LabVIEW driver have been written from the scratch in C code. In this way, the access to the hardware has been standarized to use LabVIEW for controlling every process.

B.1 The Three-tank system datasheet

B.1.1 Hardware

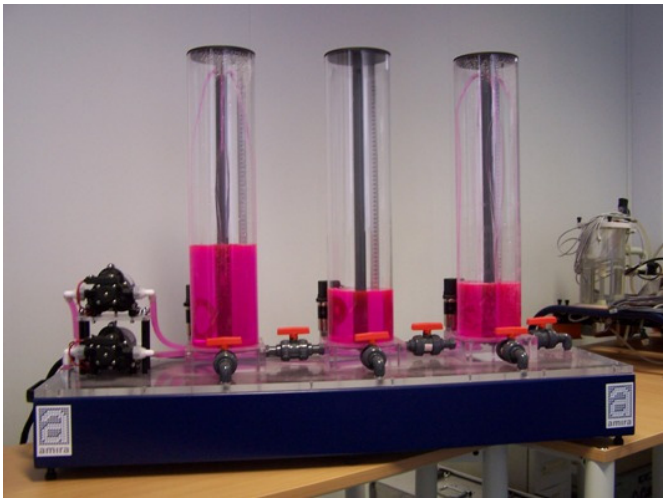


Figure B.1: Three-tank hardware in the Automatic Control Lab - UNED.

The three-tank system consists of three plexiglass-cylinders which are serially interconnected by stop valves. The pumps 1 and 2 suck distilled water from the basin, thus supplying the two cylinders on the left and right hand side of the set-up. The level of the liquid inside the three cylinders is supervised via piezo-resistive pressure sensors with integrated test amplifiers. The basin and the three cylinders present a unit manufactured out of plexiglass (see Table B.2).

Table B.1: System parameters.

Parameter	**simbol**	**value**
Cross-section of tanks	A	154000 $[mm^2]$
Cross-section pipes	S_n	50 $[mm^2]$
Outflow coeficient between valves 13	$az1$	0.38
Outflow coeficient between valves 20	$az2$	0.65
Outflow coeficient between valves 32	$az3$	0.38
Length container	$lsumi$	1300 $[mm]$
Width container	$wsumi$	360 $[mm]$
Heigth container	$hsumi$	150 $[mm]$
Gravity acceleration	g	9810 $[mm/sec^2]$

- Dimension sizes and weight of the system:
  - Length: 1270 [mm]
  - Width: 360 [mm]
  - Height: 880 [mm]
  - Weight: 40 [kg]
- Pumps:
  - Voltage: +12 [Volt]
  - Current consumption: 1.4 [A]
  - Pump performance: 7 [l/min]
  - Pressure: 1.4 [bar]
- Sensors:
  - Supply voltage: +8 [V]
  - Range: 0 ... 70 [mbar]
  - Output voltage: 1 ... 6 [V]

Actuator with signal adaption unit

The amplifier, the mains supply unit, and a signal adaption unit are contained inside of a 19”-box. The box offers a free slot for an electrical disturbance module.

- Mains:
  - 230 [V], 50/60 [Hz] on request 110 [V], 50/60 [Hz]
- Amplifier inputs:
  - Pump control signals: 0 ... +10 [V]
- Amplifier outputs:
  - Voltages for the pumps: +12 [V] (PWM)
- Inputs of the signal adaption unit:

- 3 sensor signals, range: 1 ... +6 [V]
- 2 control signals for the pumps in the range: -10 ... +10 [V]

– Outputs of the signal adaption unit:

- Liquid levels of cylinders: ±10 [V] +9 [V] = 0 [cm], -8.61 [V] = 60 [cm]
- 2 control signals for the pumps in the range: 0 ... +10 [V]

Controller (Option 200-02)

A/D-D/A-card and executable controller program for a PC with PCI slot running with WINDOWS (for WIN98SE/ME/2000/XP). The controller program provides a simple menu control (sampling period default 50 [ms], adjustable in the range 1-54 [ms]).

– Inputs: 3 sensor signals with -10/+10 [V] at 12 Bit A/D-converter.

– Outputs: 2 control signals with -10/+10 [V] at 12 Bit D/A-converter and amplifier.

Program C-source (Option 200-03)

The controller program from Option 200-02 in C++ source with library functions for graphical outputs, controlling the sampling period as well as controlling the PC adapter card requires the Borland C++ Builder V6.

Electrical disturbance module (Option 200-05)

The three sensor signals can be disrupted by switches or scaled by potentiometers. The control signals for the pumps can be scaled via potentiometers.

B.1.2 DAQ MF614 Humusoft Multifunction I/O

The MF 614 multifunction I/O card is designed to connect PC compatible computers to real electrical external signals. The MF 614 contains a 100 [kHz] throughput 12 bit A/D converter with sample/hold circuit, 4 software selectable

input ranges and 8 channel input multiplexer, 4 independent 12 bit D/A converters, 8 bit digital input port and 8 bit digital output port, 4 quadrature encoder inputs with single-ended or differential interface and 5 timers/counters.

The card is designed for standard data acquisition and control applications and optimized for use with Real Time Toolbox for MATLAB. However, in order to standarize the use of LabVIEW as a software tool to interact with hardware, a LabVIEW driver to control the card has been written (see Figure B.3).

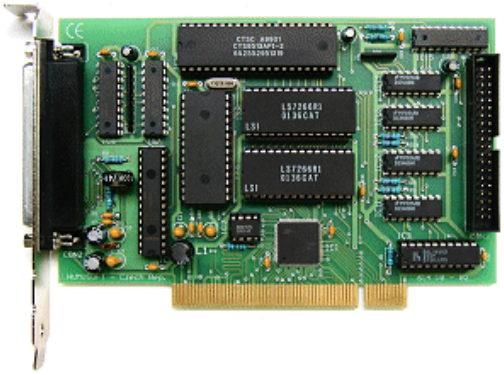


Figure B.2: Humusoft data acquisition board MF614 and LabVIEW driver.

Figure B.3: LabVIEW driver for Humusoft data acquisition board MF614.

Because of its small size and low power consumption, the MF614 can be used not only in desktop computers but also in portable computers.

- Eight single-ended 12-bit analog input channels
- Four 12-bit analog output channels

- Sampling rate up to 100 [kHz]
- 8 digital inputs, 8 digital outputs
- Programmable A/D ranges
- Four quadrature encoder inputs (differential)
- Five counters/timers
- Low power consumption
- Driver for Real Time Toolbox for MATLAB included
- Driver for Real-Time Windows Target
- Driver for xPC Target
- Driver for Windows

Specifications

- Analog Inputs
  - Channels: 8 single-ended
  - A/D converter: 12-bit, 10 [μsec] conversion time
  - Input ranges: ±10 [V], ±5 [V], 0-10 [V], 0-5 [V]
  - Trigger mode: software
  - Overvoltage: ±16 [V] max.
- Analog Outputs
  - Channels: 4 channels, 12-bit
  - Output Range: ±10 [V]
  - Output current: 10 [mA] max.
- Digital I/O
  - Input lines: 8, TTL compatible

- Output lines: 8, TTL compatible

– Timer/Counter

- Timer chip: 9513
- Timer resolution: 50 [nsec]

– Encoder Inputs

- Input channels: 4, single ended or differential
- Inputs: A, B, Index
- Input frequency: max 2.5 [MHz]

– General

- Power consumption: 100 [mA] to +5 [V], 50 [mA] to +12 and -12 [V]
- Operating temperature: 0 to 50 [$^{\circ}C$] (32 to 140 [$^{\circ}F$])
- Connector: 2 x DB-37
- Interface: PCI

B.2 The Heatflow system datasheet

B.2.1 Hardware

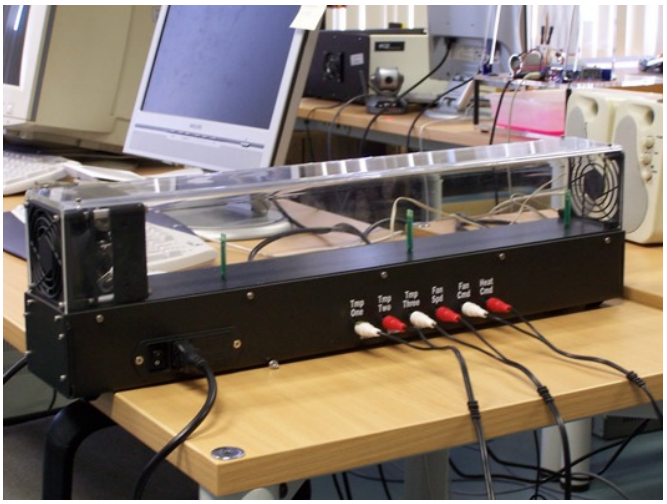


Figure B.4: Heatflow hardware in the Automatic Control Lab - UNED.

The heat-flow experiment (HFE) system consist of a duct equipped with a heater and a blower at one end and three temperature sensors located along the duct. The power delivered to the heater is controlled using an analog signal. The fan speed can also be controlled using an analog signal. Fast settling platinum temperature transducers are used to measure the temperature. Fan speed is measured using a tachometer and can be used to design speed controllers.

Table B.2: System parameters.

Parameter	Symbol	Value	Units
Heater maximum power (5V Input)	P	400	Watt
Blower maximum Airflow (at max speed)	B	46.9	CFM
Blower maximum Airflow	B_{SI}	1.33	m3/min
Maximum blower speed (5 V Input)	Fmax	3500	RPM
Minimum blower speed (1 V Input)	Fmin	2500	RPM
Tachometer calibration	Ct	1063	RPM/V
Sensor calibration	Cs	20	Deg C/V
Duct cross section area	A	0.0074	m2
Max wind speed	Ws	179	m/min
Temp sensor settling time at max wind speed	Ts	4	seconds

Table B.3: Dimensions and power requirements.

Dimensions		**Power Requirements**	
50 x 15 x 10	cm	VAC	100 - 240
0.5	Kg	Amps Max	5

Table B.4: Data acquisition requirements.

Data Acquisition Requirements		
Analog inputs	4	0 - 5 V DC
Analog outputs	2	0 - 5 V DC

Calibration

Occasionally it is necessary to calibrate the sensor measurements. To do that, a measurement of ambient temperature and a DC Voltmeter are required.

1. Power up the system.

2. Open the service panel as shown.

3. Measure S1 and adjust potentiometer P1 such that the voltage is proportional to the room temperature.

4. Measure S2 and adjust potentiometer P2 such that the voltage is proportional to the room temperature.

5. Measure S3 and adjust potentiometer P3 such that the voltage is proportional to the room temperature.

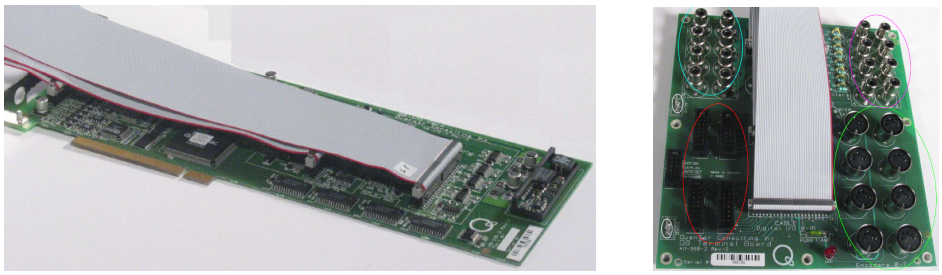
Table B.5 shows the voltages that should be obtained at various temperatures:

Table B.5: Calibration of the equipment.

Temp	19	20	21	22	23	24	25	26	27	28	29	30
Vs	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50

B.2.2 DAQ Q8 Hardware in the Loop H.I.L. Board

Figure B.5 shows the acquisition card used to control the Heatflow System. The Q8 is an innovative H.I.L. control board with an extensive range of input and output supports. A wide variety of devices with analog and digital sensors as well as quadrature encoders are easily connected to the Q8. This single-board solution is ideal for use in control systems and complex measurement applications.



(a) Q8 Hardware in the Loop H.I.L. Board. (b) Terminal board Q8.

Figure B.5: Q8 acquisition card used to control the Heatflow System.

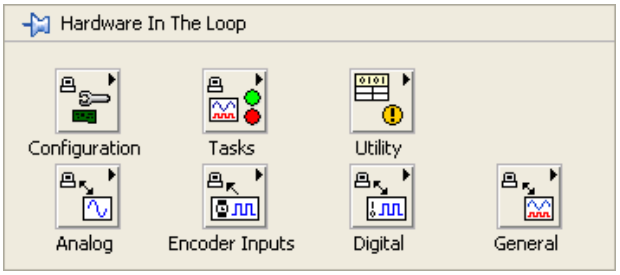


Figure B.6: LabVIEW driver for the Q8 acquisition card.

The Q8 is a versatile and powerful measurement and control board with an extensive range of input and output supports. The card can be accessed from LabVIEW programs by installing the driver (see Figure B.6).

Every Q8 is supplied complete with ribbon cables and a Terminal Board with standardized connectors, simplifying your hardware integration. The Q8 has 8 single-ended analog inputs with 14-bit resolution (sign-extended to 16 bits in hardware). With A/D conversion times of 2.4 μs/channel, simultaneous sampling and sampling frequencies of up to 350 [kHz] for 2 channels, the Q8 can handle even your most demanding performance requirements. All 8 channels can be sampled simultaneously at 100 [kHz].

The Q8 is equipped with 8 analog outputs, with software programmable voltage ranges and simultaneous update capability with an 8 [μsec] settling time over full scale 20 [V].

Aside from having 8 x 24-bit single-ended quadrature encoder inputs using TTL, CMOS, the Q8 uniquely supports simultaneous sampling of all eight encoder channels. 32 lines of individually programmable digital I/O with Totem-pole outputs provide even more high-speed performance on the Q8.

Additional features include 2 on-board PWM outputs, two 32-bit general purpose counter/timers, watchdog timers and the ability to reconfigure the 8 encoder counters as 24-bit counter/timers.

When combined with WinCon 4.0 and a PC, the Q8 yields a world of real-time control possibilities:

- Control virtually any hardware system
- Rapid Control Prototyping
- Hardware-in-the-loop control
- Monitor and control production equipment
- Development of OEM real-time applications

Key Features:

- 8 x 14-bit programmable analog inputs.
- 8x 12-bit D/A voltage outputs.
- 8 quadrature encoder inputs.
- 32 programmable digital I/O channels.
- Simultaneous sampling of both analog and encoder sections.
- 2x 32-bit dedicated counter/timers.
- 8x 24-bit reconfigurable encoder counter/timers.

- 2x on-board PWM outputs.
- 32-bit, 33 [MHz] PCI bus interface.
- Supports Quanser real-time control software WinCon (2000/XP).
- Totem Pole digital I/O for high speed.
- Easy synchronization of multiple Q8 boards.

B.3 The DC Motor datasheet

B.3.1 Hardware

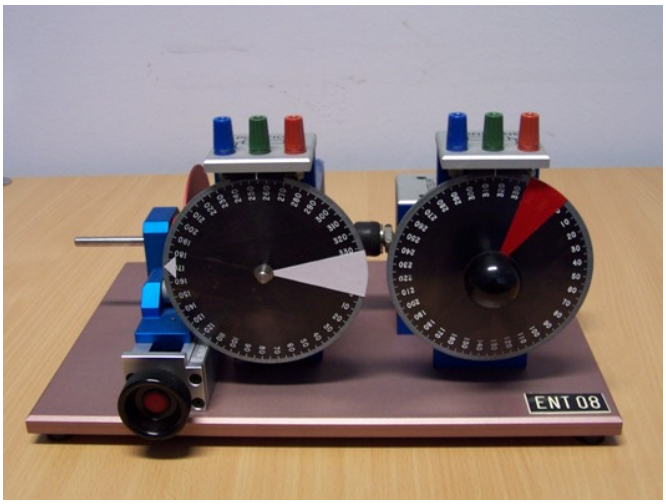


Figure B.7: DC Motor hardware in the Automatic Control Laboratory - UNED.

Figure B.7 shows the hardware components of the DC motor didactical-setup. The charge is composed of a inertia (steel disk tight to the motor's axis) and a viscous friction due to a magnetic brake. The engine is fed through a unity gain amplifier capable of delivering the power required to the motor.

A tachometer provides a voltage proportional to the angular velocity of the load. A potentiometer led through a reducer device provides a voltage proportional to its angular position. A similar potentiometer is also available to perform a eventual change of the reference directly in the equipment. Tables B.6, B.7 and B.8 show the technical features of the servo mechanism.

Table B.6: Motor parameters.

Parameter	**simbol**	**value**
Constant torque	$K\Phi$	0.030 $[Nm/A]$
Inertia (tachymeter + motor)	J_m	24x10^{-7} $[kgm^2]$
Resistance	R	5.9 $[\Omega]$
Viscous friction coeficient	f_m	3.82x10^{-6} $[Nms/rad]$

Table B.7: Steel disk parameters.

Disk	**small**	**medium**	**large**
Masse $[kg]$	0.19	0.58	1.4
Inertia J_d $[kgm^2]$	74x10^{-6}	342x10^{-6}	1440x10^{-6}

Table B.8: Other parameters.

Parameter	**value**
Tachymeter constant (C)	0.041 $[Vs/rad]$
Reductor constant (R_d)	1/60
Potentiometer constant (B)	3.37 $[V/rad]$
Magnetic brake constant (J_f)	2.7x$10^{-5}$$[kgm^2]$

B.3.2 The NI PCI-6221 Multifunction DAQ

The National Instruments PCI-6221 is a low-cost multifunction M Series data acquisition (DAQ) board optimized for cost-sensitive applications. M Series devices are compatible with the following versions (or later) of NI application software: LabVIEW, LabWindows/CVI, or Measurement Studio versions 7.x, and LabVIEW SignalExpress 2.x.

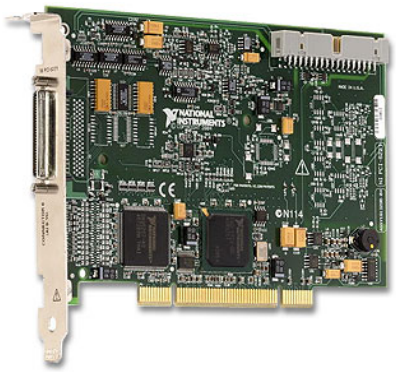


Figure B.8: The NI PCI-6221 Multifunction DAQ.

Low-cost M Series devices incorporate advanced features such as the NI-STC 2 system controller, NI-PGIA 2 programmable amplifier, and NI-MCal calibration technology to increase performance and accuracy. To learn more about M Series technologies, device specifications, and information on recommended cables and accessories, please refer to the data sheet and specifications (M-Series 2009).

Technical features

- Two 16-bit analog outputs (833 [kS/s])
- 10 digital I/O lines; 32-bit counters; digital triggering
- Correlated DIO (2 clocked lines, 1 [MHz])
- 37-pin D-Sub connector to reduce connectivty costs by 80
- Select high-speed M Series for 5X faster sampling rates or high-accuracy M Series for 4X resolution
- NI-DAQmx driver software and NI LabVIEW SignalExpress interactive data-logging software

Driver Software

M Series devices work with multiple operating systems using three driver software options including NI-DAQmx, NI-DAQmx Base, and the Measurement Hardware DDK. M Series devices are not compatible with the Traditional NI-DAQ (Legacy) driver of LabVIEW. Figure B.9 shows the NI-DAQmx driver used to control the NI-PCI6221 board from LabVIEW.

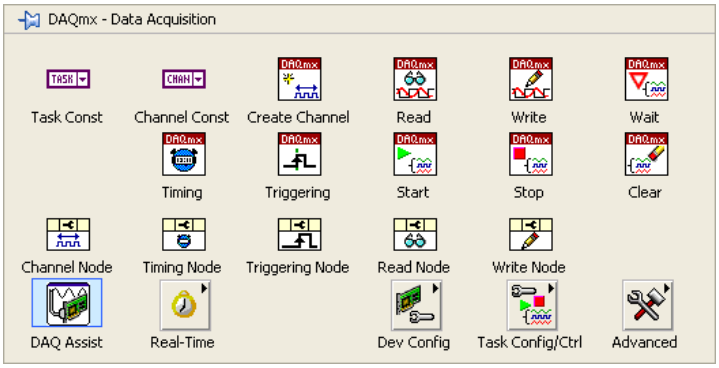


Figure B.9: LabVIEW driver DAQmx for NI PCI-6221.

Application Software

Every M Series data acquisition device includes a copy of NI LabVIEW SignalExpress so you can quickly acquire, analyze, and present data without program-

ming. In addition to LabVIEW SignalExpress, M Series data acquisition devices are compatible with the following versions (or later) of NI application software: LabVIEW 7.x, LabWindows/CVI 7.x, or Measurement Studio 7.x; or LabVIEW with the LabVIEW Real-Time Module 7.1. M Series data acquisition devices are also compatible with Visual Studio .NET, C/C++, and Visual Basic 6.

More resources and information about both DAQ board and driver software can be found in (DAQ-PCI6221 2009).

C

eMersion Management

This appendix provides information about the management of the eMersion environment from a student handling point of view. This documentation presents a summary of the available options for this platform, i.e., the options that allow a new user to start working with the remote experimentation environment and to discover other new features by himself.

Note: This information is accesible to the students performing the hands-on laboratories in the UNED from the eMersion environment.

C.1 How to work with eMersion

C.1.1 Introduction

This document aims to serve to students as a guide for the management and handling of eMersion. Through the steps described hereafter, the student will be able to carry out and complete satisfactorily a remote experimentation session.

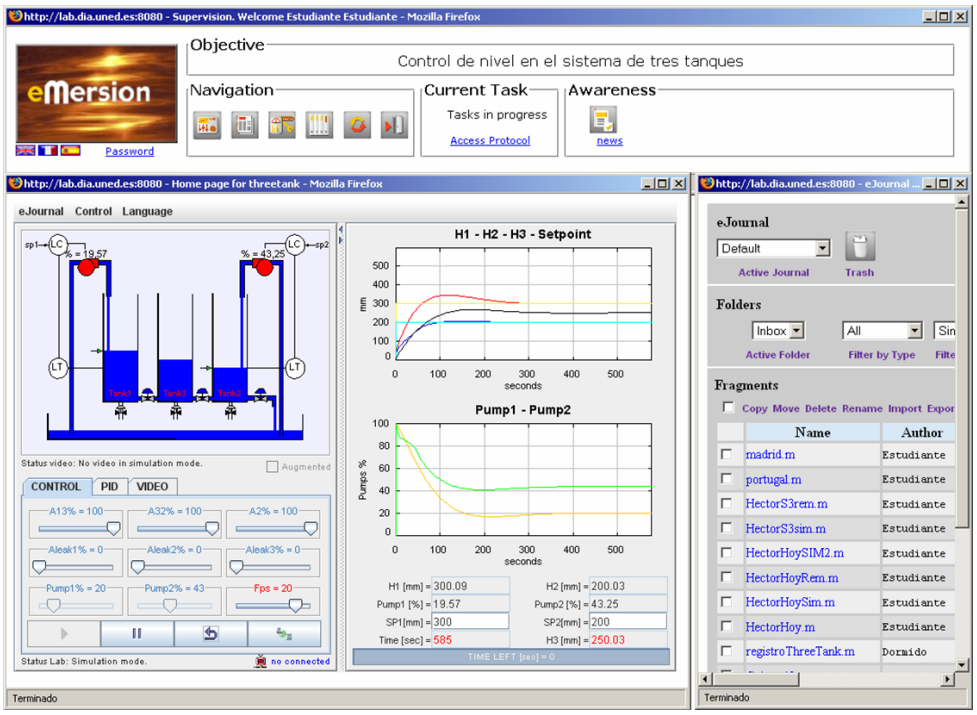


Figure C.1: Global view of the eMersion environment running the virtual laboratory corresponding to the three-tank system.

C.1.2 General description

The experimentation environment meets in its interface all the management features to support and sustain remote and virtual labs for engineering education. Thus, eMersion aims to provide a Web interface which allows students to perform their practical experiences as well as they would do in traditional f2f (face-to-face) laboratory sessions. The environment wrappes this conceptual structure taking into account that to use remote and virtual labs for engineering education is necessary to dispose of:

- The documentation associated to the experimentation module, explanations of the theory to solve the problems, brief description of the hardware to be remotely manipulated, description of the graphical user interface used to carry out the remote experiences in simulation and remote mode and, finally, a description of the experiments to perform.

- The client interface: A Java applet (created by *Ejs*) to interact with the process. By means of this GUI is possible to perform the hands-on activities using a mathematical model of the process (virtual-lab), or accessing remotely to the real plant in the lab through Internet (remote-lab).

The main features of the environment are described in the next section. The functional architecture of each module that constitutes the system is also presented.

C.1.3 Interface and eMersion functionalities

Figure C.1 shows the remote experimentation environment facade. The functionality of each work module that compose the system is described hereafter.

C.1.3.1 Navegation bar

The navegation bar is located on the top of the eMersion Web-application. This window allows users to get access to the set of Web modules which compose the environment. The *Objective* field contains a description about the fundamental objective pursued with the experimental activity. On the other hand, each icon located inside the *Navegation* area is used to access to the different Web modules of the system and, at the same time, to the documentation associated to each practice. The icons are described below:

The client interface of a remote and virtual lab (it also so-called *Telemanipulation console*) is obtained by pushing this icon. This window allows students to carry out all the laboratory experiences such as they did it in the f2f laboratory.

The *eJournal*, the collaborative and shared space for handling data fragments and user groups, is obtained by clicking on this icon. In this workspace, students can save, store, and retrieve documents, such as: work reports, images with the evolution of the experiments and/or data register (it also called fragments) for later analysis.

The third icon opens a window that contains links to external Web tools. Currently, the only link allows the access to the automatic bookings system to make time slot reservations for a later use of the remote systems.

Through this icon all the exercises and theory documentation are accesible. By clicking on it, an auxiliar window containing a link to the documentation is popped-up (see Figure C.2).

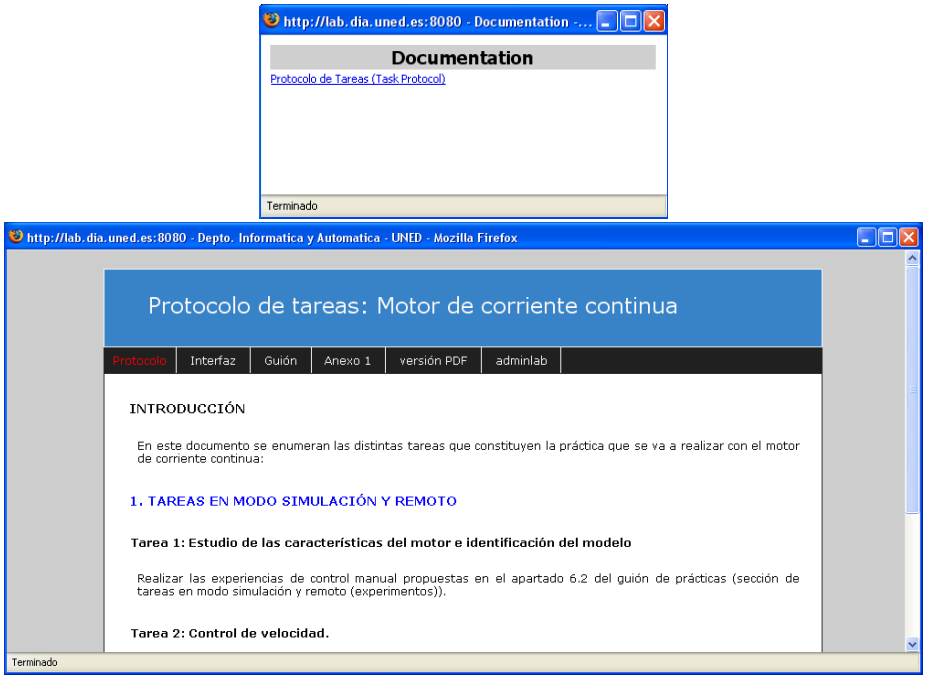

http://lab.dia.uned.es:8080 - Documentation -...
Documentation
Protocolo de Tareas (Task Protocol)
Terminado
http://lab.dia.uned.es:8080 - Depto. Informatica y Automatica - UNED - Mozilla Firefox
Protocolo de tareas: Motor de corriente continua
Protocolo
Interfaz
Guión
Anexo 1
versión PDF
adminlab
INTRODUCCIÓN
En este documento se enumeran las distintas tareas que constituyen la práctica que se va a realizar con el motor de corriente continua:
1. TAREAS EN MODO SIMULACIÓN Y REMOTO
Tarea 1: Estudio de las características del motor e identificación del modelo
Realizar las experiencias de control manual propuestas en el apartado 6.2 del guión de prácticas (sección de tareas en modo simulación y remoto (experimentos)).
Tarea 2: Control de velocidad.
Terminado

Figure C.2: Accessing to the documentation of the practice.

This documentation is structured as follows. A first link called *Protocol* contains the set of activities that a student will must carry out to complete a module (it is the first document to be consulted at starting to work). The second link called *Interface* provides a functional description for each element of the tele-

manipulation console. A third link called *Guide* contains the theory to afford the development of the required tasks (system description, mathematical model, guidelines to fullfil the sequence of activities).

Finally, two additional links are also available as appendixes. The first of them contains an brief summary about first and second order system analysis (*Appendix 1*); the second one provides a short description of the Matlab tool *ident* for system identification (*Appendix 2*).

The fifth and sixth icons refresh (update) the navegation bar and exist of the system, respectively.

The *Current task* area contains a link named *Access Protocol*. This link allows to get access to a HTML document describing how to use the eMersion environment. It also shows a indicator of the current task. Finally, the *Complements* area is reserved to include new web-components or plug-ins to the experimentation environment. Currently, only the *news* plugin is available. This functionality is used as an agenda to report news about the laboratory.

C.1.3.2 Experimentation console

As it was above mentioned, the experimentation console is the Java applet created by *Ejs*. This application allows the student to carry out their practical activities in virtual and remote mode. A complete description of the interface can be obtained from the icon (*Navegation* bar) that provides the documentation.

C.1.3.3 Working with *eJournal*

The *eJournal* is the container of the work carried out for students. Collaboration and interaction features are implemented in this space. In this shared workspace, students are going to store or retrieve their documents which can be files containing information of any kind, as for instance, data registers, image of the evolution signals scope, the state of the system, notes about experimental results, work reports, etc.

The communication between the experimentation console and the *eJournal* is performed through the sub-menu called *eJournal* that is located on the left-top part of the console. From here, it is possible to save either a graphical image of the controlled and manipulated variables of the system or a data register in a text file with extension *.m (to be loaded in the Matlab workspace). When users use these options, these data files (called *data fragments*) are automatically stored in the *eJournal*. Then, these data fragments can be used by students to generate their practical reports to be evaluated by the teaching staff.

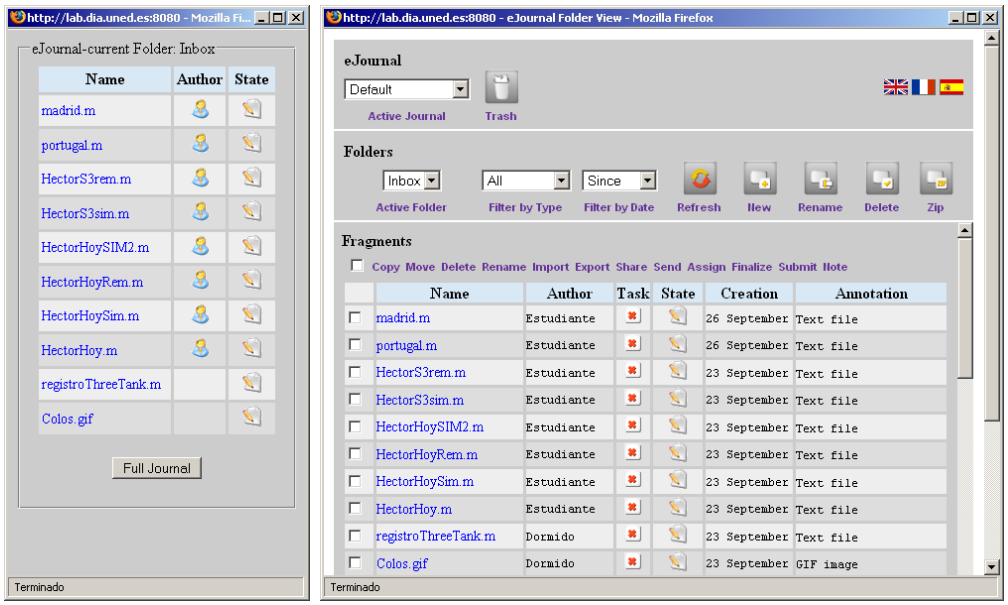


Figure C.3: Reduced (left) and extended (right) views of *eJournal*.

In eMersion, the initial view of the *eJournal* is a simplified version where students can see the last 10 fragments existing in the current folder as well as their state and authors. Figure C.3 illustrates an image of this version. Then, the student can access to the extended version by clicking on the button located in the lower part of the window. This general view shows the *eJournal* with all its functionalities divided into three different sub-spaces. The extended *eJournal* version is also shown in Figure C.3.

Subspace "eJournal"

– *Access to other eJournals*: Allows to get access to the *eJournal* of other groups (this option will be not used in this practices).

- *Trash*: The trash allows to see the data fragments deleted from the current folder. These fragments can be reloaded in the *eJournal* workspace or definitively deleted.

- *Language*: The language of the interface can be changed by pushing on the flags located on the right-top part of the interface.

Subspace "Folders"

A folder represents a directory in the workspace. The *Inbox* folder is a directory with special features. It is created automatically with the workspace and is used to receive data from the different components of eMersion as, for example, data fragments from the experimentation console. This folder can not be renamed or deleted.

It is possible to create and to rename new folders that allow students to organize the work carried out. Next, the basic functionalities of the *eJournal* in this sub-space are described hereafter:

- *Filter*: Allows to choose the type of fragment to display in the main window. There are two ways of filtering:

  - by type: There are different type of fragments. They can be: fragments (files) sent from the local hard disk of the student to his/her own workspace in the eJournal, snapshots from the evolution signals scopes (GIF images), and text files representing experimental data registers received from the experimentation console. By this option is possible to classify the fragments by these three types.

  - by date: This option allows to classify fragments depending on the creation date.

    Note: It is necessary to refresh the *eJournal* after each filtering.

- *Refresh*: Updates the main window that contains the data fragments of the *eJournal*. Each time a new fragment is saved or any thing is modified in the eJournal, pushing this button is mandatory.

- *New*: Creates a new folder. Be carefull not to use special characters of Windows operating system.
- *Rename*: Modifies the name of a folder. The *Inbox* folder can not be renamed.
- *Delete*: Eliminates a folder. The *Inbox* folder can not be deleted.

Subspace "Fragments"

The main functions in this subspace are listed below:

- *Copy*: This option allows to copy a set of fragments between *eJournals* or folders of the same *eJournal*.
- *Move*: To move data fragments between *eJournals* or from one folder to another in the same *eJournal*.
- *Delete*: By using this option, students can delete data fragments. Once deleted, they are deposited in a new space where is possible to restore or delete them definitively.

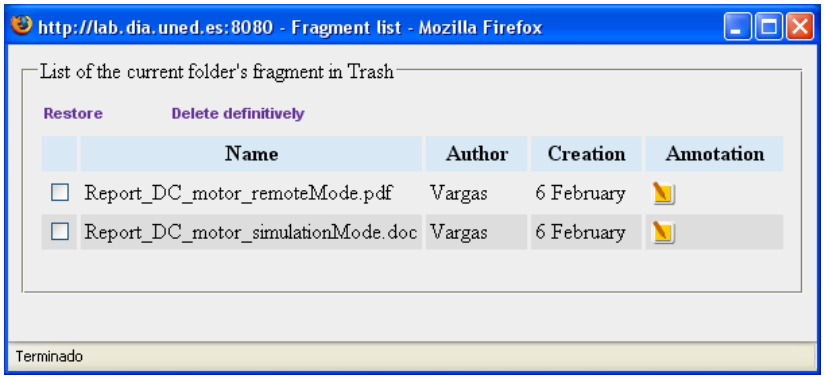


Figure C.4: The trash in the *eJournal*.

- *Rename*: This option allows to rename a data fragment.
- *Import*: This function allows to upload to *eJournal* a data fragment from the local hard disk. It is possible to attach notes to the uploaded file.
- *Export*: By using this option, students can download (export from *eJournal* point of view) fragments from *eJournal* to their local hard disk.

http://lab.dia.uned.es:8080 - Export f...
Export fragment
You can click directly on registroRealQ1.m to open or right click and choose Save Link As ... to download it to your local disk
Terminado

Figure C.5: Export fragment "registroRealQ1.m" to the local hard disk.

– *Send*: By this option, students can send messages with questions to the teacher assistants. Fragments from the workspace can be attached to the messages. Figure C.6 shows the dialog window to send a message.

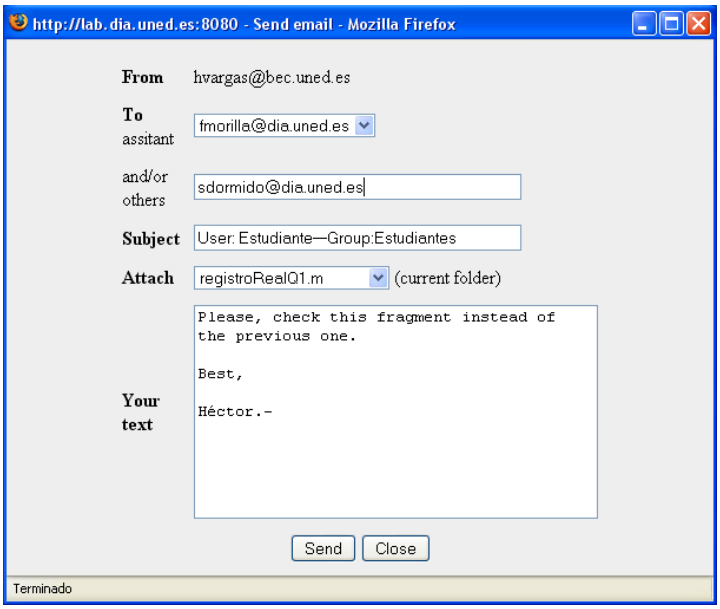


Figure C.6: Sending fragments by the dialog window *Send*.

The list of fragments is displayed in a table located at the lower part of the *eJournal* interface (see Figure C.7). The displayed files depend on the selected filter and the current work folder. It is also possible to add complementary information to the fragments to make them more comprehensibles. For instance, in this space users can find information about date time of creating of fragments, author, fragment size, etc. Even it is possible to display them in a cronological order. By dragging the mouse over a fragment, a short description about its source is shown. This information includes: the creation time, work module, task, size, etc.

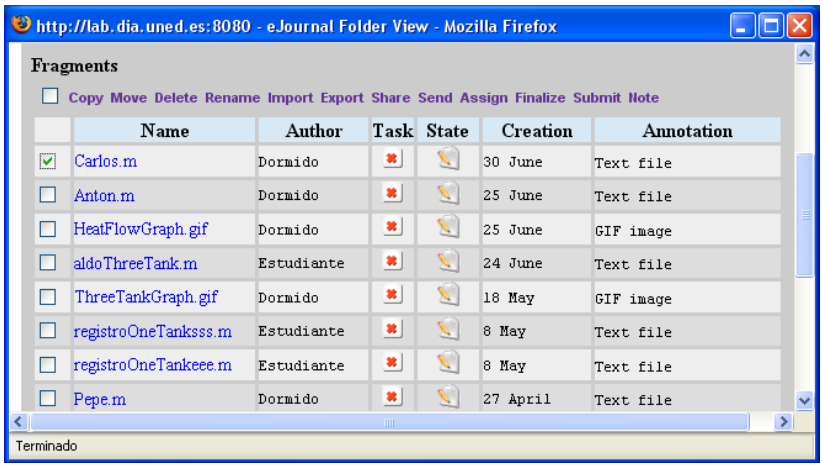

http://lab.dia.uned.es:8080 - eJournal Folder View - Mozilla Firefox
Fragments
Copy Move Delete Rename Import Export Share Send Assign Finalize Submit Note
Name Author Task State Creation Annotation
Carlos.m Dormido 30 June Text file
Anton.m Dormido 25 June Text file
HeatFlowGraph.gif Dormido 25 June GIF image
aldoThreeTank.m Estudiante 24 June Text file
ThreeTankGraph.gif Dormido 18 May GIF image
registroOneTanksss.m Estudiante 8 May Text file
registroOneTankeee.m Estudiante 8 May Text file
Pepe.m Dormido 27 April Text file
Terminado

Figure C.7: Fields description of the fragments table.

On the other hand, by clicking on a fragment users can select open or save the fragment (this action depends on the browser and type of fragment). Some basic fragment types are described below:

- *External Fragment*: Fragments imported to the *eJournal* from the user local hard disk (for example, reports in format *.doc or *.pdf).
- *Image*: Fragments of image type obtained from experimentation console. The format by default is *.gif.
- *Result*: Data registers obtained from a simulated or real experimental session. An example would be the registers *.m containing measurements.

The fields of the fragment container table provide information about each one of them:

- *Name*: Name of the fragment.
- *Author*: Owner of the fragment.
- *Task*: Shows whether fragment has been assigned to a task. The action to assign a fragment to a task is done by clicking on this simbol.
- *Status*: Helps to visualize the state of a fragment.
- *Creation*: Date and time of creating a fragment.

- *Annotation*: Allows users to associate notes to fragments. Each annotation is added as a attribute of a fragment. By this mechanism, students can generate sets of annotations associated to particular fragments. For example, the creator of the fragment can link an annotation to the fragment and make a question about the obtained results. Then, another user (or even a teacher assistant) can answer the question adding new annotations to the fragment. Figure C.8 shows the dialog window to attach comments to a fragment.

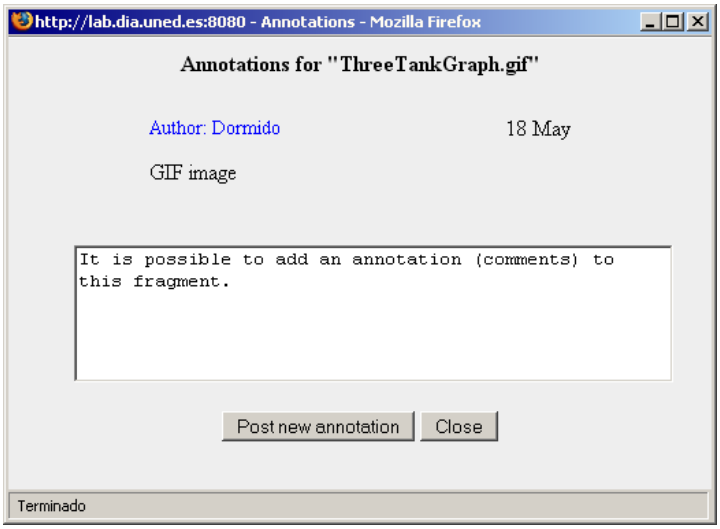


Figure C.8: Adding annotations to a fragment.